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PLEISTOCENE ICE WEDGES IN NORTH-EAST YORKSHIRE

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1. *Introduction*

THE Lower Calcareous Grit (Jurassic) outcrop on the Tabular Hills of north-east Yorkshire has for several years been the focus of intensive studies into the ecology of the moorlands associated with this geological formation. In the course of these studies air photographs have been a useful tool in the hand of the ecologist, but perhaps their most startling revelation has been that in certain parts of the moorland there is a distinctive polygonal pattern in the vegetation which had not previously been recognized on the ground. An investigation of this pattern has shown that it is almost certainly attributable to the formation of deep ice wedges in Pleistocene times, the effects of which are still reflected in the water régime of the moors, resulting in a segregation of plant communities into the distinctive pattern. It is the aim of this paper to report the observations so far made and to comment briefly on their significance.

2. *Survey of Literature on Ice Wedges and Related Frost-soil Phenomena*

(For a comprehensive account of present-day conditions of permanently frozen ground, such as must have existed over much of periglacial Europe in Pleistocene times, reference should be made to Strategic Engineering Study No. 62 by Muller (1945), published by the U.S. Army.)

An extensive and widely scattered literature on the subject of frost cracks, covering both recent and fossil examples, has now grown up. Periodically reviews have been made, notably by Leffingwell (1919), Steche (1933), Troll (1944), and Smith (1949). It is clear from these that most geologists accept as proven the case that fossil wedges seen in many parts of periglacial Europe are of the same nature as one of the

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varieties of tundra-polygons, termed ground-ice wedges and found today in such places as Alaska and northern Siberia. Nevertheless, the confusion of terminology, combined with the inevitably sporadic nature of observations, has resulted in various phenomena being included under the one term 'frost cracks'. These range from simple cracks of only a decimetre or two in depth, free of ground-ice, through small polygonal systems of the same nature, to the large networks of ground-ice such as those in Alaska described by Leffingwell. Also included in this term have been structures apparently distinct in their mode of formation such as those described by Weinburger (1944) in unconsolidated glacial gravels.

For the purpose of this paper it is proposed to ignore any possible genetical connexion between simple cracks and the ground-ice wedges and to discuss only those examples which show the wedge form, whether recent or fossil. For this reason the term 'ice wedge' is preferred to 'frost crack' for both recent and fossil structures. Even with this reservation there is considerable variation of structure.

Our knowledge of present-day ice wedges is very limited compared with the numerous examples of fossil wedges which have been described. Whereas the latter are usually known from vertical sections, the recent examples are nearly all interpreted only from surface patterns. Such patterns are most commonly polygonal, the size of the polygons ranging from 5 to 40 yards across. Usually they are hexagonal or rectangular, but other regular and irregular shapes are recorded. Good photographs of such patterns are reproduced by Weickmann (1932)—taken from the *Graf Zeppelin* during its flight over the Taimyr Peninsula in 1931—and by Washburn (1947), Högbom (1907), Polunin (1934), Taber (1943), and Cabot (1947). Brief descriptions of similar systems are given also by Gripp (1929), Paterson (1940), and Elton (1927), whilst Leffingwell, in addition to photographs, produced a plane-table map giving a very good idea of the polygonal pattern. But of these writers only two, Leffingwell and Taber, have described vertical sections of the networks, though Polunin (1932) did record ground-ice between two adjacent polygons on Akpatok Island. Leffingwell's detailed investigation has been quoted many times, but even so, an outline must be given here.

Under the intense cold of the continental winter, the frozen soil cracks into a polygonal pattern, the cracks in the first place only being a few millimetres in width and a few decimetres deep. As the surface thaws in the spring the water trickles into these cracks and freezes there, any reaching below the zone of surface thaw being preserved as ground-ice. In successive years the cracks form along the same planes of weakness, and each spring thaw adds to the ground-ice, which gradually takes on a wedge shape. At the fullest development seen today (it is a moot point whether there is a limit to their size) these wedges have a width at the top of 3 m. and reach down to an estimated 8 to 10 m. Ice intrusions this size occurring in a closed network must result in enormous pressures on the surrounding soil, and it is still a subject of discussion as to how these pressures are developed. Once the wedge has formed, the frost crack may extend into the ice itself, eventually becom-

ing filled with ice from the thaw water. Leffingwell believes that this prevents the crack closing when summer expansion takes place, so that it is the summer expansion which develops the pressure. Others (e.g. Lotze, 1932) have tacitly assumed that it is the freezing of the water in the ice crack which develops the pressure, but both Leffingwell and Taber object to this on the grounds that no pressure could be exerted in this way whilst the crack remains open at the top. In support of Leffingwell's theory is the fact that in a continental climate summer temperatures, even in regions of permanently frozen soils, may be quite high, as much as 17° C. being reached, but it may also be argued that the sudden occurrence of hard frost at the onset of the winter might seal the surface and allow internal pressure to develop in a closed system. Though the mechanism of the process must be regarded as still open to question, it suffices here to accept the plain fact that great pressures are developed.

These pressures may result in considerable distortion in the soil surrounding the wedge, and on this basis Leffingwell recognizes two types of polygon, which never occur together. The first type is recognizable on the surface by the crack being bounded by two parallel ridges perhaps 2 ft. above the general level of the ground. From sections it appears that these ridges are due to upthrust of the material from the sides of the wedges; frequently in the surrounding material, if stratified, the strata are bent upwards at the edges of the wedges. Leffingwell also suggests that the pressures developed may force the wedge itself upwards, which would contribute to this effect. In the second type of polygon, which is the only type investigated in section by Taber, there is no double ridge, but the wedges lie below channels at a lower level than the surrounding ground. In this case there is no marked disturbance of the stratification, and it is not obvious how the pressure has been relieved, unless it is by uplift of the whole soil mass. Taber, and also Dücker (1951), disagree with Leffingwell's theory of the formation of ice wedges, but this is discussed later in the light of the fossil material here to be reported.

Turning now to fossil wedges, these are by far the most abundant from the periglacial regions of Germany. Sections from sand and gravel pits, brick-earth pits, railway cuttings, and the construction of new roads have revealed numerous examples. They occur in various materials such as diluvial sands, gravels, brick-earth clay, Lias clay, Keuper marl, and even in loess. Details and illustrations of these are provided by Soergel (1932, 1936), Lotze (1932), Jonas (1938), Gripp (1929), Harrassowitz (1921), Kessler (1925), Zeuner (1935), Selzer (1936), Bahr (1932), Schmidle (1932), Brand (1938), and others. Most of these examples are somewhat smaller than the wedges known today, but since it seems that they grow gradually, and since in many instances denudation has removed the top portions, this does not vitiate the argument that they are of similar origin. A few, such as those described by Lotze and Selzer, are of comparable size, but the range is complete down to the smallest examples like those illustrated by Jonas and Bahr. Relatively few of these authors have related the wedges to any surface pattern, but

this has been most strikingly done by Selzer (1936), the pattern being very similar to present-day examples.

Outside Germany records are less numerous. To the east, Moskwitin (1940) records wedges near Smolensk in Russia, whilst typical examples are described and illustrated from the Danube plains in Hungary by Kerekes (1939). Westwards, wedges have been found in France by Bastin and Cailleux (1941)* and in Holland by Edelmann, Florschütz, and Jeswiet (1936). In Britain such phenomena had not been recognized until comparatively recently, but a number of examples are now known. These are described by Paterson (1940) near Cambridge, Arkell (1947) and Riley (1943) near Oxford, Carruthers and Anderson (1941) in north-east England, whilst Zeuner (1935) draws attention to a drawing by Skertchly (1877) which shows what is clearly a small wedge in gravels in the Fenland. The most westerly record of all is by Kilroe (1908) near Londonderry in Northern Ireland.

In many of the sections of fossil wedges the lateral upthrust, similar to that described by Leffingwell, is well seen. Soergel draws particular attention to this, but perhaps the most striking examples are those illustrated by Lotze and Selzer, in which the surrounding material is forced upwards and back on itself above the general level of the undisturbed material. This in itself is an almost infallible indication of the mode of origin of these wedges, but the overall similarity in shape (in particular the pointed apex) of the many examples quoted leaves little doubt that they are all of the same nature.

Recognition of fossil wedges is almost invariably due to a difference in the material filling the wedge compared with the surrounding material. Many of the German examples are loess-filled, but sand or silt fillings are also recorded; Bastin and Cailleux found a filling of aeolian sand and pebbles. Soergel and Zeuner record stratified fillings, but as a rule this does not seem to be the case.

It cannot be held that all fossil wedges are of equal age. Soergel (1936) describes wedges of five different periods, whilst Selzer, Gallwitz (1937), and Kerekes all illustrate wedges of different ages exposed in the same section. Cailleux (1942) has reached the conclusion that frost cracks (i.e. ice wedges) were very frequent during the last advance of the ice, but were much less frequent—though they did occur—during the retreat. They were not therefore restricted to any one glacial phase. There is no apparent reason why fossil wedges associated with an earlier extension of the ice should not be found if conditions of preservation have been favourable. Today in Alaska examples may be found of silt-filled wedges which are probably even post-glacial (Taber).

It seems to be generally agreed that the conditions favourable for the formation of ice wedges—intense cold in winter and surface thawing in summer—are those associated with a cold continental climate (Zeuner, 1945). Today their main distribution is in this type of climate, but they may occur in the same region as other types of frost soil in places where the climate is locally more continental (Elton). The significance of this

* Professor Zeuner tells me that further examples in France have recently been found at Montières, near Amiens.

with regard to the Pleistocene climate of Europe has been widely appreciated (e.g. Soergel, 1942, and Troll, 1944), and the recording of the same phenomena in Britain carries the same inferences, as pointed out by Hawkes (1940). In three recent articles Poser (1947*a*, 1947*b*, 1948) has drawn upon the evidence from frost soils of various types, glacial geomorphological features, and pollen analysis to compute the climatic conditions in periglacial Europe during the last (Würm) extension of the ice. The details of his deductions cannot concern us here, but it should be noted that he classifies fossil ice wedges into two groups according to size. The ratio of the maximum breadth to the depth (in decimetres) is used as the criterion, and it is striking that outside central Germany all the wedges are small (breadth 1–3 dm.; depth 10–20 dm.); these he terms 'Frostspalten'. In central Germany they are much larger (breadth 6–18 dm.; depth 18–80 dm.); to these he gives the name 'Lehmkeile'. He asserts that in 'Frostspalten' there is no distortion of the surrounding material, but this seems to be an oversimplification; certainly some of the smaller wedges illustrated by several authors do show some distortion of the strata, and as they also have extraneous filling material they are not simple cracks. Whilst not, therefore, accepting Poser's classification unreservedly, nevertheless the geographical distribution does appear to indicate a difference in the degree of development which must be associated with a difference in climate, the larger wedges developing under a more intensely continental climate.

The wedges to be described in this paper give a breadth/depth ratio of 15/30, which puts them without doubt into the 'Lehmkeile' category, and in this their geographical location is strikingly at variance with Poser's deductions for the Würm period. Other evidence will be produced in due course suggesting that they are of an earlier age than this 'Last Glaciation', and in this may lie an explanation of their anomalous size ratio. It is perhaps noteworthy that other wedges of large size in Britain, namely, those described by Paterson (ratio 12/33) and by Arkell (I have seen no sections of these), occur in gravels which pre-date the Last Glaciation. The Cambridge examples were covered with a further gravel deposit apparently of the same period, showing that the cracks themselves are of comparable age with the beds in which they occur.

With regard to the wedges in Yorkshire, however, their peculiar topographical position in relation to the ice-mass, which may have affected local climate, as well as the possible effect of the Pennines casting a snow-shadow over the area as a whole, are possibly reasons for regarding the occurrence of wedges here as something of a special case.

3. *Polygonal Soil Structures in Yorkshire*

The details of the vegetation associated with the polygonal pattern revealed by the air photographs will be described more fully elsewhere (Dimbleby), and it suffices here to say that the lighter tone of the 'cracks'* is due to a bog type of vegetation (largely cottongrass) contrasting with the dark tone of the background heather moor, typical of a drier situation.

* The term 'crack' so expressed signifies the linear surface depression separating two polygons; it does not refer to the wedge in the soil beneath.

More detailed interpretation of the photographs reveals a much more complete system than appears at first sight, and the accompanying diagrams (Figs. 1 and 2) show the pattern so picked out in two

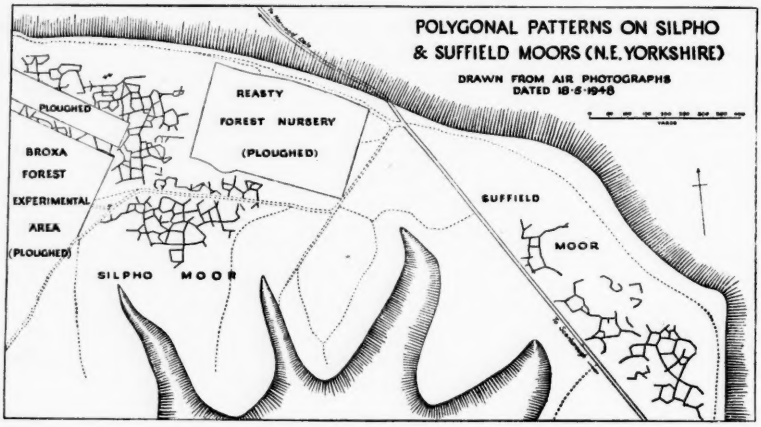

FIG. 1.

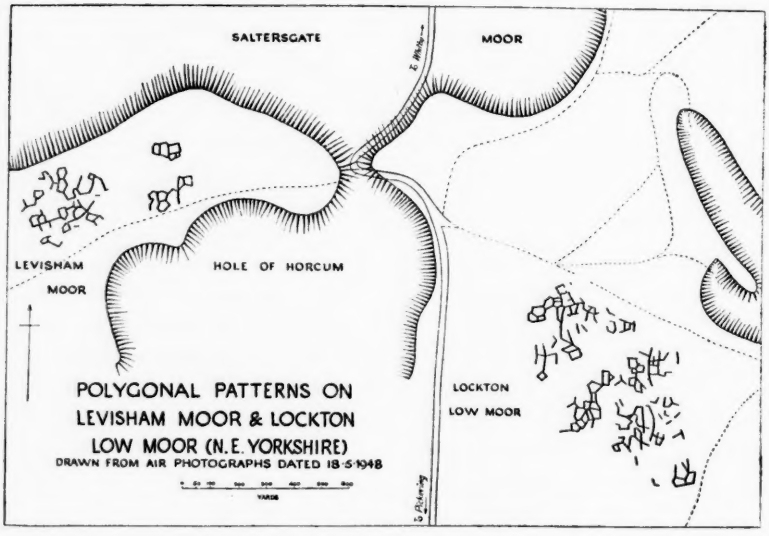

FIG. 2.

representative areas. Once it was realized that there was a definite vegetation pattern, it was possible to recognize this on the ground by paying particular attention to the nature of the vegetation, both as regards species and growth form. In fact it became possible to detect 'cracks'

which were too poorly defined to register on the air photographs. This was particularly true on the drier parts of the moor, with the result that the polygons as mapped from the air photographs tend to appear unduly large in such places. For instance, on the lower part of Silpho Moor they appear to average about 30 yards across according to the diagram, but on the ground it is clear that these larger polygons are subdivided to give a smaller network with approximately a 15-yard mesh. Nevertheless, larger undivided polygons with a diameter of 40 yards and more are found, more characteristically in the wetter parts of the moor. In other words, as one proceeds downhill from the wetter to the better-drained and drier parts of the moor the polygon size decreases.

The similarity between this pattern and that found by Riley in gravel terraces near Oxford is at once apparent. Arkell's interpretation of Riley's crop marks as frost cracks directed the present inquiry along the same lines. The ground-plan of present-day frost cracks mapped by Leffingwell (1915, 1919), the photographs of similar patterns given by

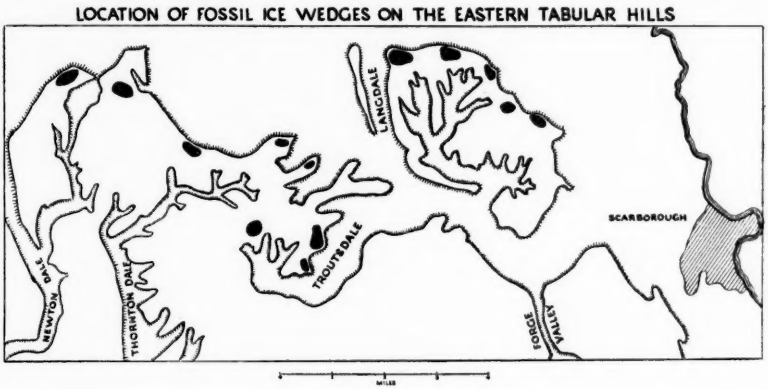

FIG. 3.

several other authors already mentioned, and the fact that they are all commensurate with the pattern in Yorkshire provided additional support to this theory. The ground pattern alone, however, is not adequate proof of the cause of this phenomenon; it was realized that only sections through the 'cracks' could produce the necessary information to establish their identity. Sections were therefore made at three separate points and exploratory pits were dug in several other places to establish the underground nature of the system.

4. *Geographical Distribution*

Close scrutiny of air photographs of the whole of the Cleveland and Tabular Hills has been made for evidence of similar systems, but those found are narrowly confined geographically and geologically. About a dozen systems in all have been located (Fig. 3), all on the flat, gradually dipping plateau formed by the Lower Calcareous Grit. None are west of Newton Dale, and in every case they are near the steep scarp.

Those on the Hackness outlier are within a hundred yards of the position of the ice-front mapped by Kendall (1902). This is not true, however, of those on the main axis of the Tabular Hills; on Lockton Low Moor they are several miles from the nearest point which the ice reached, according to Kendall. The significance of this will be discussed later.

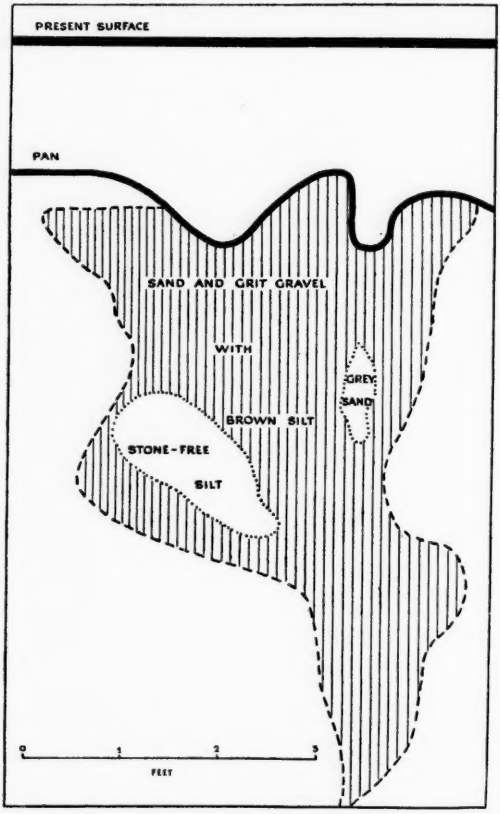

FIG. 4.

5. *Description of Sections*

Since it is possible to recognize the polygons on the ground, one could be certain that section trenches were dug at right angles to the 'crack'. The diagrams resulting from such sections are not therefore distorted by the angle at which the section cuts across the 'crack' (Soergel, 1936).

The first section cut was across one of the less conspicuous 'cracks' on Silpho Moor, towards the southern extremity of the system shown in Fig. 1. The soil is an orange-yellow sand with many stones, strongly podzolized in the upper foot or so. Vertically below the 'crack'

was encountered a more silty material with a brownish tinge, which enabled it to be recognized by eye in contrast with the local sand. This material did not extend to the surface but was first struck at a depth of 1–2 ft.; it was covered by local sand and stones. Fig. 4 shows the configuration of this intrusion in the face of the trench. The intrusion was in the shape of an irregular wedge, 4½ ft. wide at the top, tapering to an

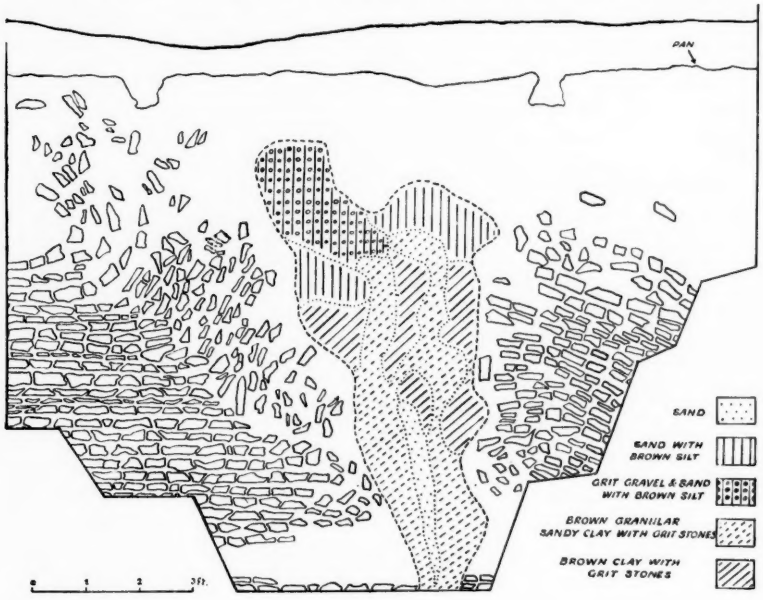
PAN
SAND
SAND WITH BROWN SILT
GRIT GRAVEL & SAND WITH BROWN SILT
BROWN GRANULAR SANDY CLAY WITH GRIT STONES
BROWN CLAY WITH GRIT STONES
0 1 2 3ft.

FIG. 5.

inch or two at about 7½ ft. below the surface of the ground. Although all except the topmost part was surrounded by the disintegrating grit rock, the rock strata at this point were not well marked, and though there was some sign of the rock having been forced upwards at the sides of the intrusion, this was not particularly noticeable.

To establish the continuity of the brown silt, two or three pits were dug at intervals along the line of the 'crack' as seen on the surface, and in each case, after passing through local material, the brown silt was encountered beneath. It was also encountered again by extending the trench across the polygon until it intersected the 'crack' on the opposite side. There can be no doubt, therefore, that this material forms a continuous system underneath the surface 'cracks'.

A second trench was dug across a 'crack' nearer the scarp on Silpho Moor, where the system was more pronounced. Here again the brownish coloration was encountered in the same way, occupying the whole of the wedge, but this wedge filling was more complex in its constitution. The nature of the intrusions will be described in more detail below. The

wedge was again about 4½ ft. wide at the top, but considerably deeper (Fig. 5); digging was not continued below 10½ ft., when the wedge was still about 9 in. wide.

In this section the most pronounced feature was the marked disruption of the regular rock strata, the stones being forced upwards and outwards. This was particularly so on the downhill side of the wedge, which itself was eccentric in this direction.

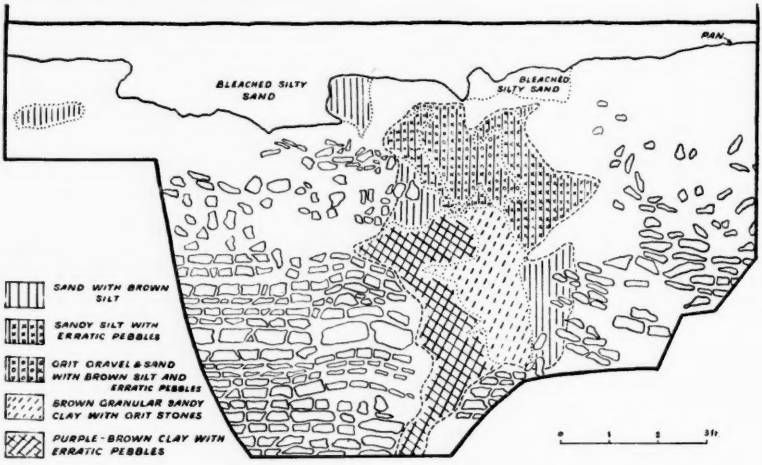
PAN
BLEACHED SILTY SAND
BLEACHED SILTY SAND
SAND WITH BROWN SILT
SANDY SILT WITH ERRATIC PEBBLES
GRIT GRAVEL & SAND WITH BROWN SILT AND ERRATIC PEBBLES
BROWN GRANULAR SANDY CLAY WITH GRIT STONES
PURPLE-BROWN CLAY WITH ERRATIC PEBBLES
3 ft.

FIG. 6.

The third section (Fig. 6) was made on Suffield Moor across a very clear-cut 'crack'. As before, the local material overlay the wedge filling, which here was even more complex and contained some pure boulder clay with numerous erratic pebbles, a material not previously recorded in fossil wedges. The wedge itself was more irregular than the others, and again eccentric in the direction of downward slope. Rock distortion was not so noticeable as in the second section, the soil being more sandy. One one side, however, there was buckling of the strata, a feature not seen in the other trenches.

The occurrence of wedge-shaped intrusions containing foreign material and the manifest signs of lateral and upward pressure can leave little doubt that here are well-marked examples of fossil ice wedges.

6. *The Filling Material*

It is the third section (Fig. 6) which gives the clue to the nature of the filling material found in the wedges. It is only in this section that the true unadulterated boulder clay is found, but it seems likely from the colour of this (a purplish-brown) that it is the origin of the brown colour found in the more silty material not only of this but of the other two sections. It seems reasonable to surmise that on the site of this section there was a greater thickness of boulder clay, so that this was carried

down into the lowest parts of the wedge in a practically pure form; the upper parts of this wedge became filled with a mixture of boulder clay and local material, much of it identical with the filling seen in the other two sections. On this assumption, the other two wedge sections occurred where the boulder clay was thinner, so that it became mixed throughout with local material. One must comment, however, on the lack of any glacial erratic pebbles in either of the first two sections.

Some additional support for the theory of a continuous boulder clay cover at some time during the Pleistocene era is provided by the occasional occurrence of small pockets of brown silty sand at about 2 ft. below the surface even in parts of the sections remote from the wedges.

It is relevant here to quote some observations made on the material filling the wedge in the first section. A mechanical analysis (pipette method; dispersion with ammonia) produced the following figures, which are set alongside those from an analysis of the local sand bounding the wedge.

	Wedge filling	*Local sand*
	%	%
Coarse sand . . .	9·1	6·9
Fine sand . . .	49·0	68·4
Silt	27·8	10·3
Clay	12·1	9·9
Loss on ignition . .	2·3	4·4

These figures bring out the difference in the clay and silt fraction of the two materials.

A further point of interest in considering the origin of the filling was obtained from a microscopical examination. In the filling from the first section were found a number of fossil microspores, unlike any pollen found today. These are totally absent from the local sand. This accords with the finding by Iversen (quoted by Jessen and Farrington, 1938) of secondary pollen of interglacial and Tertiary origin in boulder clays in Denmark. Jonas (1938) has recorded Miocene microfossils in transported clays in north-west Germany.

It is not obvious from the distribution of the various fractions of the filling within the wedge as to how the process of filling took place, but there does seem to be a general tendency towards a vertical separation of the various components. In both the first and second sections there are patches of light-coloured sand elongated in a vertical direction; it is perhaps noteworthy that in a photograph of a small wedge published by Bastin and Cailleux (1941) there is an apparently similar inclusion of lighter material. Though the filling in their case was an aeolian material, it does not follow that wind action played any part in filling the wedge.

Though the general shape of the wedges is easily enough distinguished in the sections, it is not always so easy to draw a hard line between the filling and the local material. Particularly does the filling tend to insinuate itself between the stratified stones of the bedded grit, possibly through the action of percolating water. Sloughing of the parent sand from the

sides may make for indistinctness in the boundary in the less stony places. It will be shown below that water movement in post-glacial times has been especially active down the edges of the wedges. But it is also worth bearing in mind that Leffingwell (1919) quotes examples of ice having been forced into lateral projections through the surrounding soil; if this had happened in the present case, gaps might have been left between the strata of bedded stones which would duly fill up with the new material and might produce an effect similar to that observed.

7. *Microrelief and Drainage*

Even to the naked eye there is usually detectable a difference in level between the 'crack' and the centre of the polygon on the present moor surface. On levelling, this is found to vary from an inch to nearly a foot. Moreover, the difference in actual level of the mineral soil surface may be obscured by the development of peat. Thus on Lockton Low Moor it was found that an inch of dry peat covered the centre of the polygon but the depth of peat over the 'crack' was 9 in. The width of the 'cracks' as seen on the present surface is usually 2–3 yards, though large ones may be as much as 5 yards across.

Little can be argued from this as to the land form at the time the ice wedges were active, for, as will be shown later, the land surface seen today is certainly a new one. It is suggested that the present-day 'hummocking' is secondary, and is probably the result of the passage of great quantities of water in late-glacial and post-glacial times through the disturbed rock at the edges of the wedges. In the winter it can be seen in the field that the sides of the wedges form the main water channels into the subsoil; as a result there must have been a gradual washing-down of material from above and the micro-erosion of the land surface bordering the 'cracks', all contributing to the development of the present microrelief. The apparent anomaly that the bog vegetation has developed where drainage should be freest, i.e. along the 'cracks', is simply explained by the secondary formation of an impermeable iron pan as a result of podzolization during the last 2,500 years. The hardpan usually forms at a greater depth along the 'cracks' than it does in the polygons (probably also a direct result of the freer drainage), and so produces a basin effect.

A great deal of moorland has now been ploughed and afforested in this area, which has masked, at least temporarily, any means of distinguishing the polygons by the vegetation. It has been found by Rennie, however, that even in areas long planted careful surveying of the ploughed surface may reveal a regular rise and fall of surface, the dips being at intervals which could correspond with a disturbed network system. This he has found on Wykeham Moor, an area afforested before any air photographs were taken of the district. In addition he has found a similar brown sandy silt in soil pits in this new forest, which strongly suggests that a comparable system existed there; the wedges are of course too deep to be touched even by deep ploughing.

In ordinary arable land the system may appear if the soil has at one time been podzolized. Thus in one arable field the plough has brought

up orange subsoil where the polygons were, but has not reached the old pan level along the 'cracks', so that a brownish-grey soil here contrasts with the orange, producing over the field as a whole a blurred representation of the pattern of the wedges undisturbed beneath.

Since there has been geological disturbance of the surface existing when the ice wedges were active, it is difficult to say whether the 'cracks' originally had raised edges or not. The great upthrust of stones seen in the second section suggests that they possibly had raised banks, but there is no direct proof.

8. *Position in Soil Stratigraphy*

To which period of the Pleistocene era these fossil wedges belong is a question which can only be settled by intensive geological study, but it may prove of interest to record here a few observations on the nature of the material which covers them; a fuller account will be published elsewhere. The upper 1–2 ft. of the soil are very heterogeneous, but in it three distinct zones can be distinguished in some places. Immediately superior to the wedge filling is a discontinuous layer of somewhat more clayey nature than the local sand, but containing what appear to be much weathered friable stones apparently of local material. This is interpreted as probably a solifluxion deposit, and it is separated from the next layer by a narrow, much distorted band recognizable only by the intermittent occurrence of pieces of charcoal, burnt stones, and other traces of fire. Amongst the charcoal, pine and several hardwoods, including oak, have been identified. The evidence of burning proves that this must represent an old forested surface subsequently covered over. Whether this represented an interglacial or interstadial forest the writer is not prepared to say, but the much weathered nature of the soil below this layer suggests a long exposure.

The material covering this layer is purely of local origin, mainly sand, and containing many fragments of charcoal presumably picked up from the buried forest level. Again, some form of solifluxion seems the only possible process of burial, as the slope is too gentle for hill-wash under temperate conditions of climate.

Finally, the top 3 in. or so of the mineral soil are again distinct, being more compacted and stony and containing no charcoal. Occasional glacial pebbles of non-local origin, some up to 6 in. or more in diameter, may be found in this layer only. Their origin makes a very interesting subject for speculation, particularly as they are to be found not only on the Hackness outlier but also on the main Tabular Range, several miles from the maximum extension of the ice as defined by Kendall.

It is indeed remarkable that such a shallow covering of soil should prove so complex in constitution (see idealized composite diagram, Fig. 7), and these findings must be satisfactorily accounted for in any attempt to date these wedges. It may be added that the possibility of post-glacial erosion and soil movement is practically ruled out by the fact that pollen probably dating from late-glacial times to the present day can be recognized in the top inch or two of the mineral soil.

A comparison between the erratic pebbles from the wedge filling and

those on the soil surface has very kindly been made for me by Mr. D. F. W. Baden-Powell, though only from a cursory examination. From this it would appear that the two sets are of different origin. Those from the wedges appear to have originated from a Scottish glaciation, as they contain a high proportion of Cheviot igneous rocks. By contrast, the surface erratics contain little or no Cheviot material, being made up

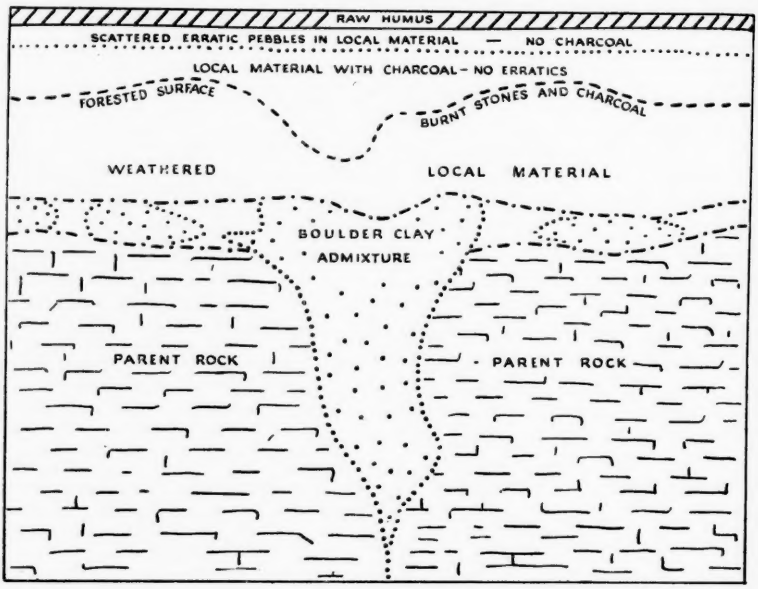

FIG. 7.

largely of quartzite or veined quartz pebbles and various grits; one pebble closely resembling the characteristic Dufton Pike granite perhaps suggests a Western influence.

Since the material in the wedges must be older than the superficial erratics, it does not seem likely that it can be coeval with the last Scottish ice in the area, as a more recent glaciation is not believed to have followed this. It is therefore possible that the boulder clay in the wedges was laid down by an earlier Scottish glaciation.

It is impossible to assess the thickness of this deposit of boulder clay, though it was probably only thin. Whether frost cracks and ice wedges could have developed in the parent rock under such a covering is a moot point. Even if they did, the absence of any weathered material or charcoal in the wedges suggests that they cannot post-date the subsequent interglacial. If they formed before the boulder clay was laid down, the ground-ice must have remained until the transgression and recession had passed, when the final thaw would melt the wedges and allow the clay to enter the gaps so formed, together with local material sloughed

from the sides. In either case the wedges seem to be correlated in time with this ice-cover, though whether they formed immediately before or immediately after it cannot be established with certainty.

To summarize, there are four separate points of evidence suggesting that these wedges are not contemporary with the Last Glaciation: the evidence of the erratic pebbles; the association with a boulder clay in a situation which was not ice-covered in the Last Glaciation; the complex stratigraphy of the soil overlying them; and the anomalous size of the wedges in comparison with continental examples attributable with certainty to the Würm glaciation. Alone, none of these is, perhaps, incontrovertible, but taken together they point strongly to the formation of these wedges in an earlier glaciation.

9. *Problems of Formation*

Comparison of these structures in Yorkshire with the many other examples of both contemporary and fossil ice wedges leaves no doubt as to the identity of their nature. Whilst it is not strictly within the writer's province to express any opinion as to how, when, and under what conditions these wedges were formed, it is nevertheless clear that their situation and the material in which they occur must cast doubt on some of the theories of origin which have been expressed. Broadly, these theories fall into two categories. That propounded by Leffingwell (1915, 1919) assumes that the water which is segregated into the ice wedges comes from above and percolates downwards; whether the lateral pressure exerted by this water is due to summer expansion, as believed by Leffingwell, or to the forces exerted by freezing, as held by several other writers, cannot be settled here. The other hypothesis is that put forward by Taber (1943), and also accepted by Dücker (1951), who maintain that the descending zone of frost at the onset of a cold climatic period will effectively seal the surface against the downward penetration of moisture from the surface. On this assumption, the water additional to that held in the soil itself, which is quite inadequate to account for the large volume of ice segregated, must come from below, from ground water. It is an essential feature of this theory that conditions favouring the development of ice veins will therefore be met with in fine materials such as silts with a high capillarity.

It is true that the majority of instances of ice veins or ice wedges today are in situations where there is ground water, such as low-lying river flood-plains or sea-coast flats, but Taber says that any satisfactory theory must explain all contingencies. The fossil cracks described here occur on an elevated plateau of sandstone, several hundred feet above any ground water today, in a material with only a small silt and clay content and therefore with low capillarity. Any attempt to postulate a high water-table arising from an ice front abutting on the scarp must break down on the grounds that under the severe cold necessary to form ground ice, no free water could be produced from the ice wall.

A further example of frost polygons in a very similar situation is that described by Polunin (1932, 1934) on Akpatok Island. Here they occur on a high limestone plateau, extending from the very edge of a sheer

cliff to about 80 yards inland. Certainly there can be no ground water there today, yet ground-ice is present now and the polygons are of the type investigated by Taber. It might be maintained that these are fossil, but Polunin considers this unlikely. He thinks that the reason for this being the only locality on the island where such polygons ('giant polygons' as opposed to 'stone polygons') occur is that it is the only place where the soil is deep and bears a thick layer of humus muck on the top. This focuses attention on the surface rather than on the subsoil and suggests the greater likelihood of Leffingwell's theory applying in such places.

It seems probable that there may be more than one process capable of producing ground-ice. Taber's hypothesis explains most of the phenomena he has himself examined, but there are a number of grounds, apart from those just given, for believing that it cannot be universal. The following may briefly be mentioned.

i. If ice veins are forming from sheet ground-ice parallel with the surface, no upward movement of soil or ice could take place, except *en masse*. But in fact strata may be violently distorted and material pushed upwards; this may be due to the actual rise of the wedge itself, which Leffingwell believes to happen, as much as to the lateral pressure. Taber weakly classes such upthrust as secondary and admits that he has never sectioned a polygon with raised edges. Dücker rejects Leffingwell's theory entirely on the grounds that, in his opinion, it does not explain this frequently observed upthrust, but in its place he accepts Taber's theory, which not only fails to offer any explanation of this very phenomenon but is based on material which does not even exhibit it.

ii. Taber pertinently points out that at a depth of 5–10 ft. temperature changes in the soil are inadequate to explain deep cracking. But is it not possible that the development of a small wedge in the region of great temperature change may in fact prise the deeper layers of the frozen soil apart, the crack extending down as the wedge grows?

iii. In his own observations Taber says he has never seen a crack in an ice wedge itself, and one would expect the ice to crack more easily than the soil. Leffingwell (1919) in fact does illustrate just such cracks in the ice.

It is important to establish a probability between these two theories respecting the material here presented, and the balance certainly seems to be in favour of Leffingwell's frost crack theory, but it must be left to glaciologists to decide how the great pressures so clearly demonstrated in these sections are developed, and how the void left by the melting ice became filled with boulder clay.

Finally, there is the problem of how the boulder clay itself reached the area. If it is confirmed that the cracks on Lockton Low Moor and elsewhere do in fact contain material of this origin, obviously the accepted theories of the unglaciated nature of the region as a whole are called into serious question. It may have to be allowed that Kendall's delineation of the ice margin only applies to the latest extension of the ice and that an earlier glacial phase was more extensive. Even so, the glacial pebbles found in the uppermost layers of the soil today cannot be

explained this way. Clearly much still remains to be discovered about the glaciology of this most interesting region.

10. *Summary*

Through the medium of air photography an elaborate network of bog vegetation has been revealed on the heather moors on the eastern Tabular Hills of north-east Yorkshire. Sections of the soil under this vegetation pattern have revealed that it is due to a buried system of Pleistocene ice wedges. These wedges are occurring in stratified sandstone, which shows great disruption at the sides of the wedges, indicative of enormous upward and lateral pressure. The wedges themselves are now filled either with boulder clay or a mixture of boulder clay and local material. Since this occurs on a supposedly unglaciated area, some readjustment of glaciological theory in this area seems inevitable. The wedge filling is itself covered by a shallow but complex deposit of local material which includes a buried forest layer represented by charcoal and other traces of fire at the buried surface. This calls for consideration in any attempt to establish the glacial age of the fossil ice wedges. Some problems of the mode of formation of the wedges are briefly discussed.

Acknowledgements

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A STUDY OF ROCK WEATHERING WITH REFERENCE TO THE SOILS OF THE MALVERN HILLS

PART I. WEATHERING OF BIOTITITE AND GRANITE

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WITH TWO PLATES

Introduction

FROM the viewpoint of petrology soil may be regarded as the residuum resulting from the disintegration and decomposition of rocks under the influence of climate and vegetation. Many of the primary rock minerals result from processes occurring at depth and at high temperatures and pressures, but their alteration in the soil occurs at the surface of the earth at low energy levels. While minerals in rocks are mainly broken down initially under the influence of reactive aqueous solutions penetrating intercrystalline cracks, their further decomposition occurs under the more immediate influence of the chemical and physical conditions resulting from the additional interplay of climate and vegetation with which they are in metastable equilibrium. The minerals in a soil may therefore be described in terms of the common rock-forming minerals and their secondary products of weathering.

The soils chosen for this study are from the Malvern Hills in Worcestershire, England. The hills are formed of a narrow ridge of hard crystalline rocks, presumably of Pre-Cambrian age, rising abruptly from the flat Triassic plain on the east (Plate I, A), and passing into the hill-and-dale country of the Silurian and Old Red Sandstone formations on the west. The range lies in a north to south direction, is about 9 miles long, and nowhere exceeds 1 mile in width. The elevation ranges from about 700 ft. to 1,395 ft. at Worcestershire Beacon. The district studied lies between the Wyche Cutting in the south and Worcestershire Beacon in the north. The area is a suitable one for weathering studies, as it was not traversed by any large ice-sheet, so there is no glacial drift to introduce ambiguities into the relationship of soil, subsoil, and bedrock. In addition the suite of rocks is comprehensive, varying from granite to ultra-basic rocks rich in hornblende and biotite.

On a broad scheme of classification, all the soils would be included in the Major Soil Group of Brown Earths. They are, in general, shallow, very stony, and carry a dense turf covering. A tendency to excessive drainage is shown by their dry fluffy nature, and appears to be conditioned by two main factors: their coarse mineral texture, and the ready percolation of rain-water through the faults and fractures characteristic of the underlying rocks.

The mineralogical changes which occur during the formation of soil from two contrasted rock-types, granite and biotitite, found in proximity

in the field, are described in this paper. A similar study of representatives of the hornblendic rocks will be presented in a later communication.

Experimental

Preparation of samples. In preparing the soils for mineralogical analysis the following procedure was adopted. The clay ($< 2\mu$) was first separated from the soil by an adaptation of the beaker method of mechanical analysis as described by Piper (1944). The silt ($20–2\mu$) was also separated from the same sample by sedimentation after the removal of the clay. The residue of sand was divided into two size-grades by sieving, corresponding approximately to 2·0–0·2 mm. (coarse sand) and 0·2–0·02 mm. (fine sand).

Petrographic examinations. Thin sections prepared from fresh and weathered rock samples were used to characterize optically the composition of the parent rocks and the initial stages of mineral breakdown. Heavy liquid separations of the sand fractions of the soils were made, the liquid consisting of a mixture of acetylene tetrabromide and nitrobenzene standardized at s.g. $2{\cdot}90 \pm 0{\cdot}01$: this effects a separation of the hydrous micas, chlorites, feldspars, and quartz from the heavier minerals. The soils were not treated with hydrogen peroxide to remove organic matter as they contain vermiculitic minerals readily exfoliated by peroxide; this pre-treatment would have yielded very false estimates of their relative abundance in microscopic counts.

X-ray analysis. The two methods used were the 'oriented-aggregate' (Nagelschmidt, 1941) and powder techniques, using filtered copper radiation and a 90-mm. powder camera of the type described by MacEwan (1949). In order to facilitate the examination of the clays by the aggregate technique it is desirable to remove both organic matter and free oxides and hydroxides of iron and aluminium, since their presence not only obscures the diffraction pattern, but also adversely affects the orientation of the flaky minerals. The organic matter was destroyed by treatment with hot hydrogen peroxide. The 'free' iron compounds were removed by the method proposed by Galabutskaya and Govorova (1934) which employs sodium hydrosulphite ($Na_2S_2O_4$). This method compares favourably with others suggested and appears to have little (if any) effect on the clay minerals.

Field Data

In the Malvern crystalline-complex veins of coarsely crystalline to pegmatitic biotitite occur,* which in places consist of 80 per cent. or more of coarse biotite in flakes up to an inch or more in diameter. Such veins are well exposed in the main Tolgate (N) Quarry, north of the Wyche Cutting. An exposure in a slip at the top of the quarry yields a very satisfactory profile of the residual soil, only slightly contaminated with granitic material. The biotitite occurs as a vein-like mass (at this locality sheared), about 4 ft. wide, flanked by granitic country rock

* A brief note on the field occurrence has been given by R. W. Pocock, A. Brammall, and W. N. Croft (1940).

(Plate I, B). Even at the lowest level exposed (about 4 ft. 6 in.) the rock is highly weathered and can easily be dug with a spade. At 12–15 in. from the surface there is a fairly sharp boundary between the rock and the overlying soil.

The residual soil over the granite is very shallow and stony in comparison with the deeper soil on the more readily weathered biotitite, and rubbly granite fragments are abundant even in the surface soil. Both soils are freely drained, their porous nature allowing water to percolate readily. They are acid in reaction, the pH range being 3·6–3·8 in the granite soil and 4·6–4·9 in the biotitite soil.

Petrography of the Parent Rocks

Biotitite. In the fresh rock the biotite occurs in large brown glistening flakes and is normally free from any alteration products. Optical examination of thin sections from a block of weathering biotitite shows clearly the alteration of the biotite to a green optically negative chlorite. The alteration begins around the margin and along the cleavage traces of the biotite and gradually proceeds inwards, resulting in the formation of a chloritic pseudomorph. X-ray diagrams of the chlorite flakes, photographed with the (001) plane parallel to the beam, show a pattern similar to that given by artificially oriented aggregates of clays (Nagelschmidt, 1941). It appears therefore that on weathering the biotite breaks down into a polycrystalline aggregate of a chloritic material, with a marked preferential orientation corresponding to that of the original mica.

The chloritization of the biotite is accompanied by the segregation of the liberated titania in association with lime and silica into abundant crystallites of secondary sphene (Plate II, A), normally occurring in feathery groupings and needle-shaped aggregates. Iron oxides, finely granular yellow pleochroic epidote, and calcite occur sparingly as weathering products.

A micrometric analysis of five micro-sections of the weathered rock underlying the profile sampled gives the following modal composition (volume per cent.): biotite (chloritized) 57·0, amphibole 24·5, epidote, zoisite, and clinozoisite 6·7, iron ore (magnetite and ilmenite) 4·6, clinochlore 3·0, sphene 2·5, apatite, quartz, a sodic plagioclase, rutile, and calcite 1·7.

The chloritized biotite occurs in greenish, moderately pleochroic flakes, up to 5 mm. in size, rather bent, often fractured, and showing a marked excretion of iron oxides (Plate II, B). The optical properties, determined on flakes separated from the weathered rock at a depth of 30–36 in., are slightly variable, but all the flakes are sensibly uniaxial and optically negative. Average values for the refractive indices are n_β $(= n_\gamma) = 1{\cdot}590 \pm 0{\cdot}003$; birefringence 0·003–0·004. A relationship to penninite is suggested by the low birefringence and the 'ultra-blue' abnormal interference colours, which according to Winchell (1933) are characteristic of this variety of chlorite.

On X-ray analysis the flakes give a typical chlorite-type diagram with four orders of the 14·2 Å basal reflection of about equal intensity and the

fifth weak (Fig. 1, A). Vermiculites also give a strong 14 Å basal reflection but with weak second and third orders. This enables a distinction to be drawn between chlorite and vermiculite, and indicates the dominantly chloritic nature of the flakes. After heating at 540° C. for several hours, the first-order basal reflection develops a 'tail', becoming

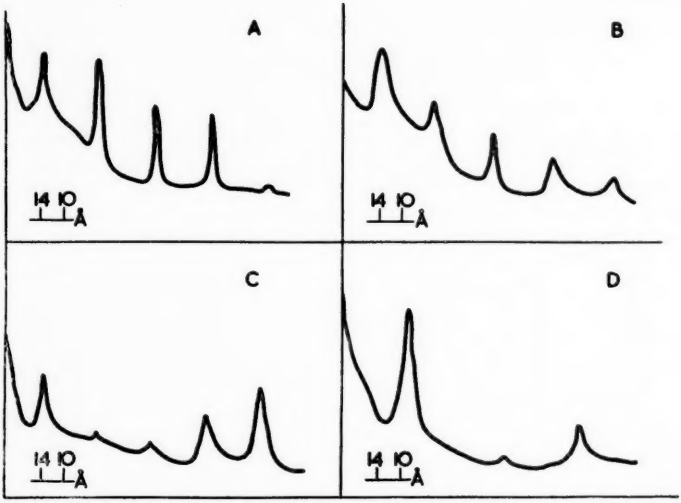

FIG. 1. Microphotometer tracings of X-ray diagrams of (A) coarse flakes from weathered biotitite, and (B) the same after heating at 540° C. for several hours; (C) brownish micaceous flakes from sand fractions of overlying soil, and (D) the same after heating at 750° C. for several hours.

asymmetrical towards higher angles, and all the spacings become diffuse except the third order (Fig. 1, B). This behaviour suggests that (1) a random mixture is present, a *small* amount of material occurring with layers of smaller spacing than the chlorite, and (2) the spacing of the third order, i.e. 4·72 Å, is almost exactly a submultiple of the smaller spacing. Thus the smaller spacing must be close to $4{\cdot}72 \times 2 = 9{\cdot}44$ Å. This figure corresponds closely to the spacing obtained on heating vermiculite to the same temperature, indicating the presence of some vermiculite-like units interleaved in the chlorite structure. The later suggestion is confirmed by the ready exfoliation of the flakes in cold hydrogen peroxide (cf. Groves, 1939).

The exchange capacity, determined on material lightly ground to pass the 120 I.M.M. sieve, is 28 m.e./100 g. Values for vermiculites (Barshad, 1948) are about 140 m.e./100 g.; therefore assuming no exchange capacity for chlorites, the amount of interleaved vermiculite layers is of the order of 20 per cent.

The other constituent present in the rock in appreciable amount is a tremolitic amphibole occurring in long-bladed, often interlocking crystals which in section are either colourless or show slight pleochroic

variation from pale green to colourless. It is highly resistant to weathering and is concentrated in the sand fractions of the soil.

Granite. Under the microscope the texture is typically granitic, all the constituents being allotriomorphic. A mineral analysis of the unweathered rock underlying the profile sampled gives the modal composition (average of 7 micro-sections): quartz 23·0, feldspar (microcline-perthite, oligoclase, orthoclase) 64·0, penninite 6·0, epidote-clinozoisite 3·2, iron ore 1·3, amphibole, sphene, apatite, &c., 2·5.

The most abundant feldspar is microcline, in part perthitic, occurring in plates up to about 5 mm. in size, showing the typical polysynthetic twinning in two directions (Plate II, C), and also occasionally a major twinning of the Carlsbad type. Even in sections of the weathered rock the microcline is always fresh when the other feldspars are considerably altered. The orthoclase is always turbid and clouded with secondary products. The plagioclase is a usually twinned oligoclase or oligoclase-andesine. Since it has been altered in part to an irregular network of white mica (Plate II, D), present in the unweathered facies, it has apparently been subjected to hydrothermal processes.

The quartz crystals occur in mosaic intergrowths, the individual crystals being of smaller grain size than the surrounding feldspar. The crystals normally show undulatory extinction, and frequently contain liquid and dust-like inclusions (Plate II, D).

At this locality the granite is slightly contaminated by the incorporation of xenolithic basic material, now represented hydrothermally by aggregates of mafic minerals (Plate II, D). The minerals comprising these basic 'clots' are chlorite (penninite), yellow pleochroic epidote and clinozoisite, magnetite, brownish sphene, and apatite. The chlorite occurs as well-developed plates up to 2 mm. in size with the following optical characteristics: pleochroic with $X = Y =$ green $> Z =$ very pale yellowish-green, birefringence very low, anomalous chocolate-brown interference colours, negative elongation, and positive optic sign. Alteration of the chlorite, as seen in sections of the weathered rock, results in the formation of optically negative yellowish-brown to brown pseudomorphs of a vermiculitic character.

Minerals present in small amounts include biotite, usually as irregular-shaped chloritized flakes, a pale green to colourless amphibole, allanite (?), garnet, and zircon. Primary muscovite is rare in the granite at the locality sampled, although elsewhere it is locally abundant, very large pockets of coarse muscovite-pegmatite occurring at several points in the Tolgate–Wyche area.

Trend of Alteration in the Sand Fractions

Minerals occurring in the 'light separates' (s.g. $< 2{\cdot}90$) of the sands of the soils are quartz, feldspar, chlorite-vermiculite, white mica (sericite), and chalcedony, but their relative amounts differ markedly in the two profiles dependent on the character of the underlying rock. This is illustrated in Fig. 2 for the fine sands,* where chlorite-vermiculite

* Percentages are based on microscopic counts of approximately 500 particles in about 25 random fields for each sample.

are the dominant minerals in the biotitite soil, while quartz and feldspar approximate to 85 per cent. in the granite soil. The proportions are similar in the coarse sands, but this fraction is unsuitable for detailed mineral analysis owing to the occurrence of large amounts of composite mineral aggregates. Minerals present in small amounts in both profiles

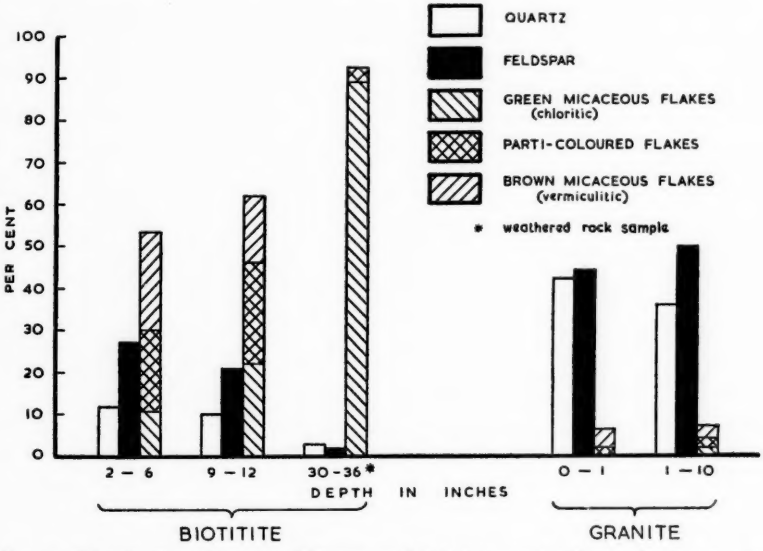

FIG. 2. Distribution of quartz, feldspar, and chlorite-vermiculite in the fine sands of soils overlying biotitite and granite.

are sericite and chalcedony (very rare). In the granite soil, sericite occurs as colourless micaceous flakes, about equal in amount to the chlorite-vermiculite, but of smaller grain size. It is rare in the biotitite soil.

As quartz and feldspar occur only in accessory amounts in the biotitite, their presence in the overlying soil is due largely to contamination from the neighbouring granite. It seems very probable, however, that the data imply more contamination than exists, due to the stability of these grains compared with that of the micaceous minerals.

A characteristic feature of this soil is the presence of yellowish-brown to brown micaceous flakes with a golden or bronzy lustre. Their X-ray diagrams are distinct from those of the chloritic flakes characteristic of the underlying rock in that they have strong first, fourth, and fifth orders of the basal reflection, and weak second and third orders (Fig. 1, C). On heat treatment at 750° C., the first-order basal reflection at 14·32 Å is condensed to 9·45 Å (Fig. 1, D), consistent with data given by Gruner (1934) and Barshad (1948) for vermiculites.

Optically the flakes are fairly strongly pleochroic with X = very pale yellowish-brown $< Y = Z$ = brown. The acute bisectrix is nearly

normal to (001) as in biotite, and (−) $2V$ attains a maximum of 8°. Refractive indices are n_α 1·563, n_β ($= n_\gamma$) 1·582±0·003; birefringence 0·019. These values correspond closely with data given by Shannon (1928) for a sample of vermiculite (jefferisite) from West Chester, Pa., but are considerably lower than those given by Walker (1949) for vermiculite occurring in the soils of north-east Scotland.

The transition from the dominantly chloritic weathering product of biotite to the vermiculite in the sands is shown by a progressive colour change from green to yellowish-brown. The trend of alteration is shown in Fig. 2, in which these minerals have been subdivided on a colour basis. Such a division is approximate, but the colour is a fairly reliable guide, while X-ray and optical examinations suggest that there is a continuous gradation. Essentially only the green chloritic type occurs in the weathered rock, but the vermiculite becomes increasingly frequent in passing into the soil.

The 'heavy separate' (s.g. > 2·90) of the fine sands of the biotitite soil is more than 55 per cent. by weight in both layers of the profile, and is characterized by a 'flood' of amphibole (over 80 per cent.). The principal subordinate minerals are members of the epidote-clinozoisite group, iron oxides and sphene. A few grains of zircon, rutile, and apatite are also present.

By contrast, the amount of heavy residue in the corresponding fractions of the granite soil is small, being 8 per cent. in the 0–1 in. layer and 5 per cent. in the basal soil, the low percentage being due to the small amounts of ferromagnesian minerals in the parent rock. In order of relative abundance, epidote-clinozoisite, amphibole, and iron oxides make up the bulk of the separate. Garnet, zircon, and sphene are the commonest of the remaining minerals. Tourmaline, kyanite, and apatite are rare. Apatite forms from 3–4 per cent. of the heavy residue from samples of the powdered rock, but was not observed in the surface soil. Its elimination is doubtless due to the acid conditions under which weathering is taking place.

Clay Mineralogy

Biotitite. The X-ray reflections given by oriented aggregates of the clays from the weathered rock and from the surface soil are shown in Fig. 3.

The diagrams of the unheated clays show an integral series of (00*l*) reflections with spacings of approximately 14 Å and submultiples. The basal spacing and the intensity of the first five lines of the (00*l*) series are given in Table 1.

The spacings are not affected by treatment with glycerol, which excludes the possibility that montmorillonite (MacEwan, 1944) or 'swelling chlorite' (Stephen and MacEwan, 1950) contributes to the 14 Å line. Of the known clay minerals, the remaining possibilities are chlorite and vermiculite.

The recordings (A) and (C) in Fig. 3 are very similar and in both cases, heat treatment increases the intensity of the fifth-order basal reflection and eliminates the second and third orders. The first-order basal

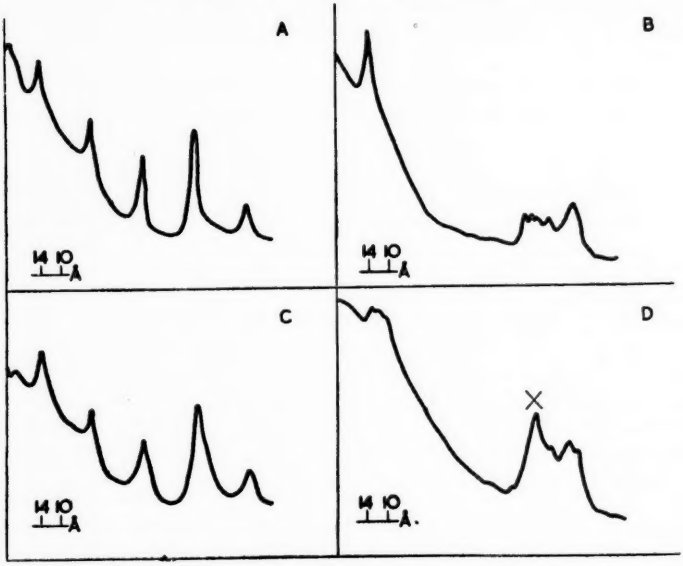

FIG. 3. Microphotometer tracings of X-ray diagrams of clay from the weathered biotitite, (A) before and (B) after heating at 540° C.; and from the surface soil, (C) before and (D) after similar heat treatment.

TABLE I

Basal Spacing and Intensity of Basal Reflections

	Soil clay 2–6 in.	*Soil clay 9–12 in.*	*Clay from rock 30–36 in.*
Basal spacing (Å)	14·08	14·07	14·06
Order		*Intensity*	
1	s	s	ms
2	m	m	m
3	m	m	m
4	ms	ms	ms
5	w	w	w

Note: X-ray intensities, estimated visually, are given on the following scale: very strong (vs), strong (s), medium-strong (ms), medium (m), medium-weak (mw), weak (w), very weak (vw).

reflection develops a composite structure, a feature which is particularly marked in (D).

The structures developed on the outer (low-spacing) side of the 14 Å line were analysed in the following way (Fig. 4). The curve was re-plotted on a horizontal base line to eliminate the background. The peak near 14 Å was then completed assuming that it is symmetrical and that the inner (high-spacing) edge represents its true shape. The peak

thus obtained was subtracted from the curve and the residue re-plotted. The process was repeated on this curve and continued until the residue itself was symmetrical.

This analysis reveals that four peaks are present in the clays from both the weathered rock and the soils. The clays from the soils give peaks at

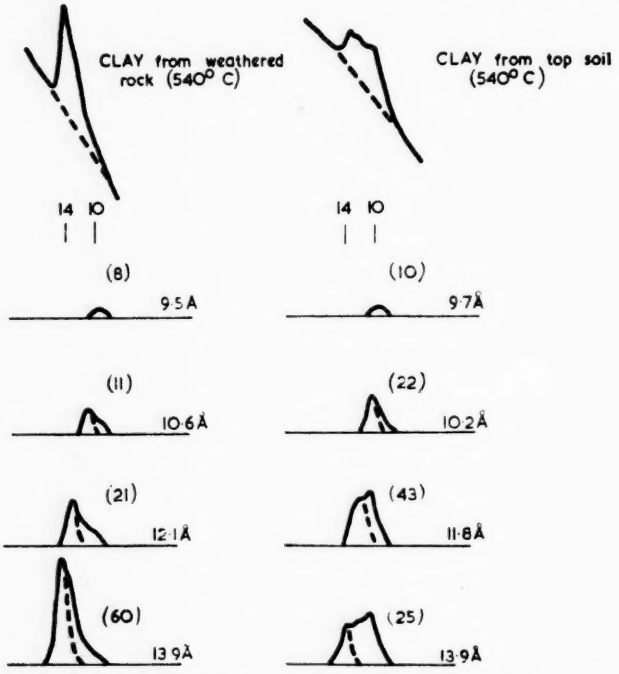

FIG. 4. Analyses of the peaks in the 10–14 Å region of heat-treated clays from the weathered biotitite and top soil. Figures in brackets give the areas of individual peaks as a percentage of the total area of the curve.

identical spacings, namely, 9·7, 10·2, 11·8, and 13·9 Å, and it is probable that these same peaks are also present in the clay from the weathered rock, the small differences in spacings observed being due to experimental error.

These results may be most readily interpreted on the basis that there are *three* main crystalline phases present, namely:

(*a*) a chloritic phase giving a 13·9 Å reflection on heating;
(*b*) a vermiculitic phase giving an approximately 10 Å reflection on heating;
(*c*) a random mixture of (*a*) and (*b*) in roughly equal proportions. Little significance is attached to the lower spacing at 9·5–9·7 Å, as it is very broad and its magnitude is of the order of the experimental error.

The structure of the heated chlorite (*a*) is analogous to that observed in penninite and other magnesian chlorites heated at a higher temperature (Brindley and Ali, 1950). When penninite was heated at 600° C., marked changes occurred in the intensities of the basal reflections, the (001) reflection becoming much more intense, while (002), (003), and (004) were considerably weakened. The position of the lines, however, remained essentially the same, and the structure was still that of a chlorite. Brindley and Ali have explained the change in intensities by migration of the interlamellar magnesium ions, resulting in a MgO-like structure between the main sheets.

The vermiculitic phase (*b*) is probably a 'potassium vermiculite', which gives a mica structure on heat treatment. The evidence for its presence is the strong basal reflection at approximately 10 Å with the development of the strong third-order basal reflection at 3·33 Å (x, Fig. 3, D) in the band which develops at 3·47–2·80 Å, the limits of this band corresponding approximately to the fourth and fifth orders of the original structure. The material cannot be a *fully* saturated potassium-vermiculite, as Barshad (1948) has shown that this, unheated, gives a diagram similar to that of biotite-phlogopite and shows no 'expanded state'. It is probable, however, that sufficient potassium ions are associated with the main sheets to stabilize the structure at a mica-spacing after heat treatment. The 9·5–9·7 Å reflection may then be explained as due to a small proportion of true vermiculite, i.e. without potassium ions.

A photograph of the clay from the surface soil, after saturation with potassium ions, but without heating, shows two components, unchanged chlorite and a mixture of chloritic and mica-like layers, which is in full accord with the proposed composition.

The proportions of the 14 Å (chloritic) and 10 Å (vermiculitic) components can be determined by measuring the area under each peak (Fig. 4), the 12 Å peak being taken to represent a random mixture of approximately equal parts of the components. The results are shown in Table 2, the proportions being given to the nearest 5 per cent.

TABLE 2

Calculated Proportions of Chloritic and Vermiculitic Layers as determined by Heating at 540° C., and applying Theory of Diffraction by Randomly Mixed Layers

	% *Chlorite* (*14 Å*)	% *Vermiculite* (*10 Å*)	% *'Residue'* (*9·5–9·7 Å*)
Clay from soil (2–6 in.)	45	45	10
Clay from soil (9–12 in.)	40	50	10
Clay from weathered rock (30–36 in.)	70	20	10

It has been assumed in these calculations that the 10 and 14 Å peaks have the same absolute intensity, so that the peak area is proportional

to the amount present. Any correction, however, for actual intrinsic intensity will not affect the conclusions regarding the changes in *relative* amounts of the components in the different layers of the profile. It will be noted that the proportion of vermiculitic layers is higher in the soil clays than in the clay from the weathered rock, but does not alter appreciably between the lower and upper soil layers.

Powder photographs of the clays show a marked similarity to that of penninite, but with fewer lines: this is probably due to randomness in the structure, which is accounted for by the presence of vermiculitic layers.

Granite. X-ray diagrams of oriented aggregates of the soil clays show a prominent series of basal reflections of 10 Å and submultiples, indicating a mineral of the mica group (illite),* and weaker reflections at 7·1 and 3·5 Å which can mainly be referred to a kaolin mineral (Fig. 5, A). By heating at 540° C. the kaolin lines are eliminated, and a pattern is left with strong basal reflections at 10, 5, and 3·33 Å referable to mica, and very weak lines at 13·8 and 11·8 Å attributable to a chlorite-vermiculite crystallization (Fig. 5, B). The latter appears to be identical with the type of clay material composing the soil clays over the biotitite. Quartz is present in accessory amount, the strong reflection at 3·35 Å being superimposed on the third-order basal mica reflection, and a weak reflection at 4·26 Å can be seen on the tracings (Fig. 5, A and B).

The illite is dominantly (or exclusively) of the dioctahedral (muscovite-like) variety, as is shown by the strong second-order basal reflection at 5 Å (Nagelschmidt, 1937) and the strong (060) line at 1·49 Å (MacEwan, 1949). It will be noted on the aggregate photograph (Fig. 5, A) that the illite basal reflection at 10 Å is somewhat asymmetrical, being sharp on the outer edge but forming a 'tail' towards lower angles. This 'tail' is eliminated after heating at 540° C. (Fig. 5, B), from which it can be assumed that it is due to hydration of the illite caused by the interpolation of layers of water molecules between the structural sheets, suggesting that the illite is tending to break down to a montmorillonitic product. The absence of a reflection at 17·7 Å in glycerol-saturated samples shows, however, that true montmorillonite is not present.

It has not been possible to ascertain the type of kaolin mineral present, as the amount is too small to discriminate between kaolinite proper and the 'fireclay mineral' described by Brindley and Robinson (1947). The presence of halloysite is improbable owing to the sharpness of the reflections. By comparing photographs of mixtures of hydromuscovite and kaolinite in definite proportions with those of the unheated aggregates, the amount of kaolin in the clays is estimated to be 15 ± 5 per cent.

The clays show only slight variation in the amounts of the different minerals present, kaolin and quartz, however, being slightly more abundant relative to the other minerals in the surface soil than in the basal layer. X-ray diagrams of coarse (2–$0{\cdot}5\,\mu$) and fine ($< 0{\cdot}5\,\mu$) clay, however, show a marked differentiation, the quartz and chlorite

* Grim, Bray, and Bradley (1937) proposed the term *illite* as a general one for the mica-like clay mineral of argillaceous sediments.

being concentrated in the coarser clay, and being essentially absent in the finer clay, which consists almost exclusively of illite and kaolin.

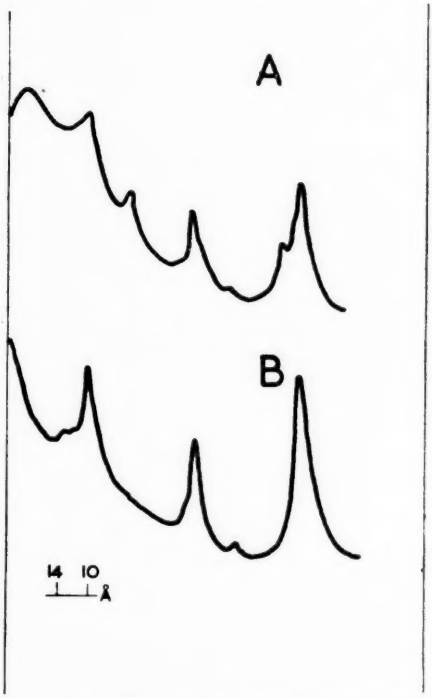

FIG. 5. Microphotometer tracings of X-ray diagrams of the clay from the basal layer of the granite soil, (A) before and (B) after heating at 540° C.

Discussion

The observations show that as weathering proceeds in the biotitite soil, the dominantly chloritic material of the weathered rock is being converted into a vermiculitic material, this being so for both the coarse flakes of weathered biotite and the clays. These results and those of previous workers show the common occurrence of the process of *vermiculitization* in the weathering of primary biotite. The vermiculitic product may apparently be reached either through mixed-layer mica-vermiculite intermediate stages (Kerr, 1930; Wager, 1944; Walker, 1949), or mixed-layer biotite-chlorite and chlorite-vermiculite stages as shown here. The relationship between chlorite and vermiculite and the probable mechanism of the transition will be discussed in Part II of this communication.

The dominant mineral in the clay of the granite soil is a member of the dioctahedral illite (clay-muscovite) group, whose presence can be

attributed to the alteration of the feldspar of the bedrock. The alteration appears to be in part hydrothermal and in part due to weathering. It is difficult, if not impossible, to draw a definite boundary between these processes. In the apparently unweathered granite, shred-like white mica is widespread as a secondary mineral derived mainly from the acid plagioclase, and the orthoclase is turbid and clouded with secondary products. It appears very probable that this pre-weathering alteration 'initiates or facilitates the subsequent alteration by dilute solutions at normal temperatures and pressures' (Bosazza, 1948).

Dioctahedral illites contain the same major elements as potash feldspars, and it is probable that in the early stages of weathering much of the potassium liberated by the breakdown of the latter is 'fixed' by a reaction involving the accompanying alumina and silica, the resulting product being an aluminiferous member of the illite group. The alteration of plagioclase to illite probably requires the introduction of potassium from external sources, although in acid plagioclases potassium is commonly present in some quantity.

Crystalline constituents of the clays occurring in minor amounts are minerals of the chlorite-vermiculite crystallization, whose presence can be related to the weathering of the basic contaminants. The small amount of quartz is attributable to the physical breakdown of crystals present in the parent bedrock.

Summary

The importance of the parent bedrock in determining the mineralogical composition of the derived soils is shown by the present study. This is true both for the coarser 'inherited' mineral particles and also for the clays which may be assumed to represent the 'weathering complex', the latter in the biotitite soil being a chlorite-vermiculite crystallization, while in the granite soil it is dominantly an illite-kaolin association.

Acknowledgements

The writer wishes to express his indebtedness to Dr. A. Brammall for advice which greatly facilitated the choice of the most suitable sites for sampling, and for his continued interest during the progress of the work. The helpful criticism and encouragement given by Dr. A. Muir must be acknowledged. Thanks are also due to Dr. D. M. C. MacEwan for useful discussion on the interpretation of X-ray data. This paper is based on part of a thesis approved by the University of London for the Ph.D. Degree.

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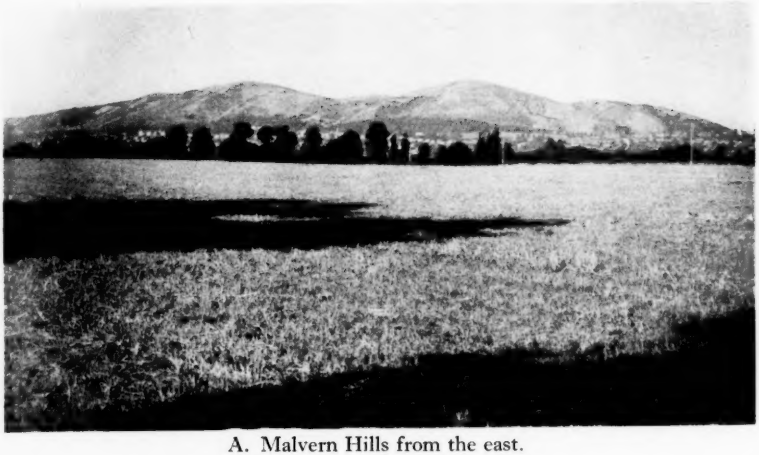
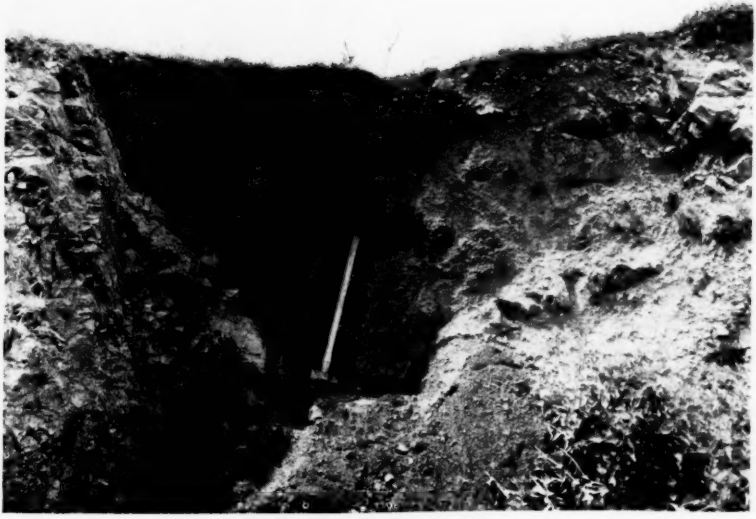


A. Malvern Hills from the east.

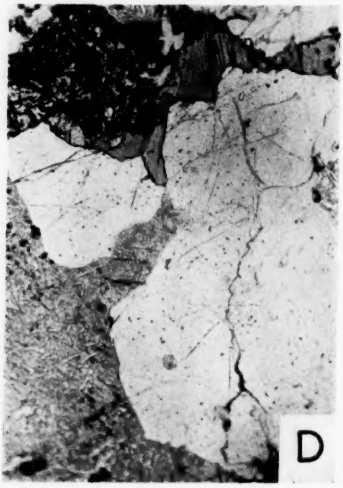


B. Residual biotitite profile.

I. STEPHEN—PLATE I

A. Weathering biotitite phenocryst. Dark areas are original biotite, surrounded by secondary chlorite enclosing abundant crystallites of sphene. Ordinary light, × 50.

B. Biotitite. The bent and fractured nature of the flakes is well seen. The other constituents are a tremolitic amphibole, iron oxide, and sphene. Ordinary light, × 50.



C. Microcline, in granite, showing polysynthetic twinning. Crossed nicols, × 50.

D. Granite, showing aggregate structure of the dark minerals (top of field). The minerals of these basic 'clots' are epidote, chlorite, magnetite, sphene, and apatite. The other constituents are highly sericitized plagioclase (bottom left), and quartz with characteristic inclusions. Ordinary light, × 50.

Photomicrographs by V. Stansfield, F.R.P.S.

I. STEPHEN—PLATE II

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THE ELECTROCHEMICAL CHARACTER OF THE CLAY MINERAL ILLITE AND ITS RELATION TO THAT OF MUSCOVITE

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Introduction

MANY soils, clays, and shales have been found to contain mica-like clay minerals now known in the literature as illite or hydrous mica. As the latter name suggests, they are structurally similar to muscovite, but contain more water and less potassium than the latter. Like the other clay minerals, illite is usually identified in soils and other argillaceous sediments by such physical methods as X-ray and thermal analyses. However, no less important than its identification is the question of an unequivocal definition of its fundamental electrochemical character *vis-à-vis* the other clay minerals, inasmuch as the electrochemical character provides the real clue to an understanding of such important physical and chemical properties of clays as base exchange and water relationships. The central connecting theme in the electrochemistry of clays is their dominant acid character which finds expression in their capacity to combine with and retain bases, and for this reason studies of the titration curves of clays as acid systems, i.e. as the so-called hydrogen clays, would constitute the most logical approach to their electrochemical character. However, the available information concerning the titration curves of illite is rather meagre compared with what we know of the other clay minerals (Mitra, 1942; Mitra, Bagchi, and Ray, 1943; Marshall and Bergman, 1942*a*; Marshall and Bergman, 1942*b*; Marshall and Caldwell, 1947), and what is more significant is the fact that in spite of the close relationship between illite and muscovite suggested by their X-ray diffraction patterns and chemical compositions, no attempt has yet been made to examine this relationship in the light of their electrochemical behaviour as acid systems. Our work on the titration curves of hydrogen mica (Mitra and Rajagopalan, 1948) encouraged us to take up this comparative study, and our results recorded below fully bear out the expected relationship between illite and muscovite in so far as their acid character is concerned.

Methods

Green lumps of illite obtained from Dr. S. B. Hendricks through the courtesy of Dr. S. P. Raichaudhuri of the Indian Agricultural Research Institute were powdered and suspended in faintly alkaline distilled water. The fraction containing particles with equivalent spherical diameter smaller than 2·0 microns was separated by decantation and

then centrifuged to obtain particles smaller than 0·4 micron. The hydrogen or acid form of this fraction was prepared by repeatedly leaching it with 0·02*N* HCl and then washing free from chlorides. On shaking with water, the hydrogen illite readily gave a stable suspension. For the potentiometric work, hydrogen and glass electrodes were used in conjunction with saturated calomel electrodes as the reference half-cell. 'Continuous' as well as 'bottle' titrations as explained below were done. In a continuous titration, changes of the pH were measured following additions of increasing amounts of the base to a given volume of the sol kept in an atmosphere of pure hydrogen or nitrogen gas. A fresh addition of the base was not made till the e.m.f. after the previous addition remained constant to within 1·0 millivolt for a period of at least 15 minutes. In a 'bottle' titration, increasing amounts of the base were added to a fixed volume of the sol contained in each of several Jena glass bottles, the mixtures were kept overnight, and their pH's separately determined on the following day. The bottle titrations, by allowing a long time of interaction between the hydrogen illite and the base, made it certain that the resulting titration curve truly depicted equilibrium conditions. Both the continuous and bottle titration techniques gave almost identical titration curves up to a pH of about 8·0. Above this pH, the reaction between the hydrogen illite and the base became very slow and recourse had to be taken to the bottle titration technique.

Results and Discussion

Fig. 1 shows the titration curves obtained up to a pH of about 9·5 using the continuous titration technique. The potentiometric titration curve with $Ba(OH)_2$ shows a weak inflexion at about pH 5·5 and a more pronounced one in the neighbourhood of pH 7·5. The base exchange capacities (b.e.c.) calculated at these inflexions are, respectively, 11·0 and 20·0 milliequivalents per 100 g. of the hydrogen illite. The conductometric titration curve with $Ba(OH)_2$ shows a break corresponding to the first inflexion in the potentiometric curve. The conductometric titration was not extended to obtain the second inflexion. The KOH-curve (potentiometric) shows the second inflexion, but it fails to bring out the first weak one. The first inflexion is, however, noticeable when titration with KOH is done after addition of sufficient solid KCl to the sol to give a normal concentration of the salt in the mixture (Fig. 2). Titration with $Ba(OH)_2$ in the presence of *N* $BaCl_2$ also gives both the inflexions.

The run of the titration curve, the pH's at the inflexions and the b.e.c.'s calculated from them depend, to some extent, on the base used and on whether a neutral salt is also present, illustrating the part played by adsorption of cations in the interactions of H^+ ions on surfaces with bases (Mitra, 1942).

The titration curves given in the figures, particularly the $Ba(OH)_2$-curve and the curves obtained on titration in the presence of salts, show a buffering beyond the second inflexion. As already mentioned, the

hydrogen illite takes part in a very slow reaction with the base above pH 8·0. The course of this reaction is revealed by the 'bottle titration' curve given in Fig. 3.

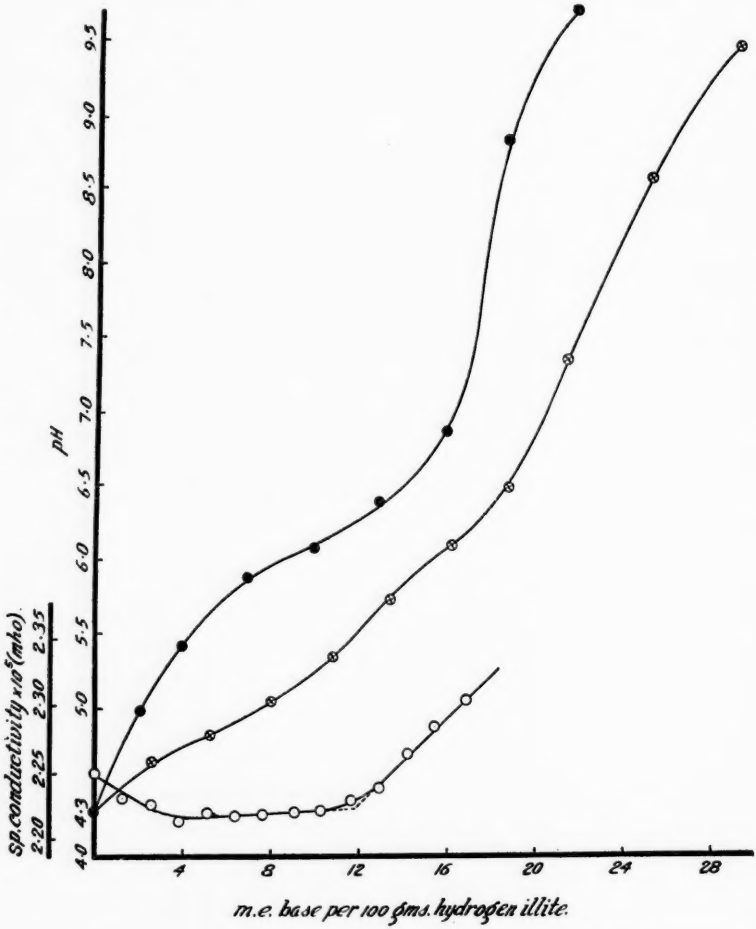

FIG. 1. Titration curves of hydrogen illite ('continuous' titration); ● KOH, ⊗ $Ba(OH)_2$-potentiometric; ○ $Ba(OH)_2$-conductometric.

This titration curve shows, in addition to the second inflexion found at about 20·0 m.e. of the added base, a third rather weak inflexion in the neighbourhood of pH 11·0. This inflexion gives a b.e.c. of about 60·0 m.e. per 100 g. The b.e.c.'s at the third and second inflexions are, therefore, as 3 : 1.

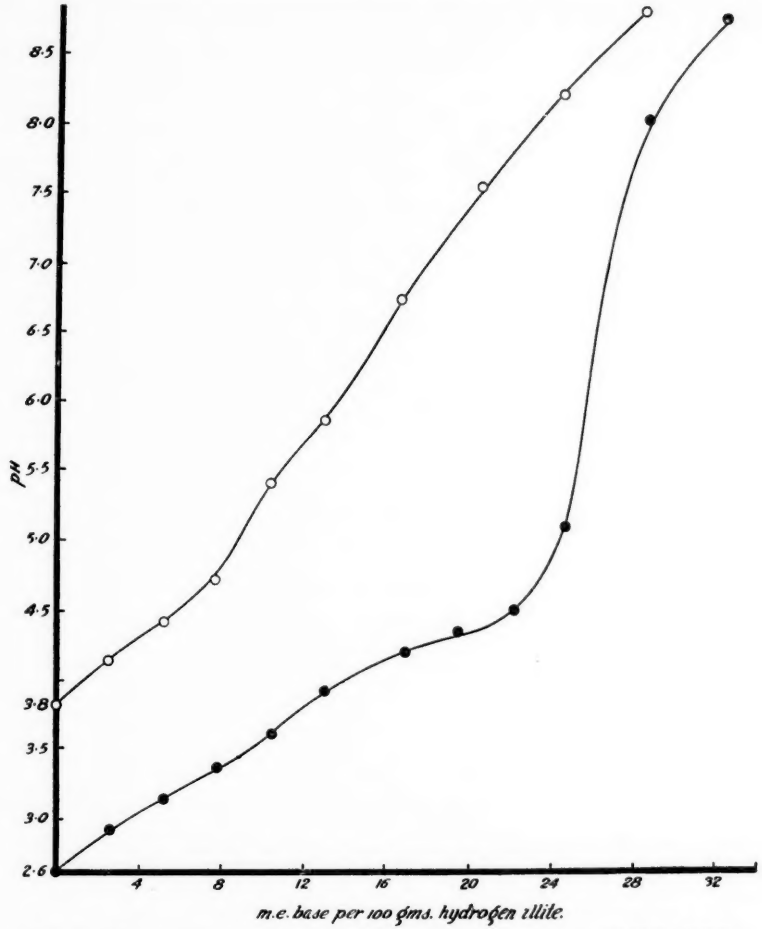

FIG. 2. Titration curves of hydrogen illite containing salts: ○ *N* KCl, KOH; ● *N* $BaCl_2$, $Ba(OH)_2$.

Similarity with Muscovite

Very similar observations were made by us (Mitra and Rajagopalan, 1948) on titrating hydrogen muscovite, i.e. ground muscovite whose exposed K^+ ions had been replaced by H^+ ions on continued treatment with a dilute mineral acid. Of particular interest was the fact that, as now found in the case of hydrogen illite, the b.e.c.'s at the third and second inflexions were, within experimental errors, as 3 : 1. The significance of this observation in the case of the hydrogen mica became clear from the fact that the second inflexion in the titration curve gave a b.e.c. which was exactly equivalent to the quantity of K^+ ions displaced from

the muscovite when the latter was leached with a dilute acid to prepare the hydrogen system. This agreement showed that the second inflexion in the titration curve of the hydrogen mica marked the completion of the

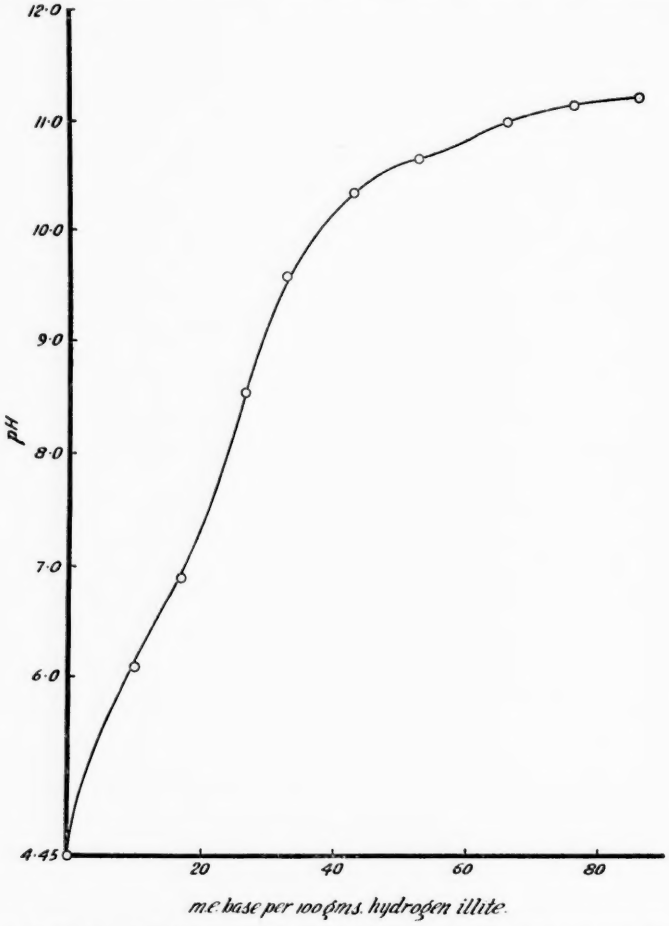

FIG. 3. Complete titration curve of hydrogen illite ('bottle' titration) with KOH.

neutralization of H^+ ions acquired by the surface of the mica particles in exchange for their exposed K^+ ions when the hydrogen system was prepared. Such H^+ ions were of course bonded to the surface by negative charges arising from the isomorphous replacement of every fourth Si^{+4} ion in the tetrahedral layer of the mica lattice by an Al^{+3} ion. The fact that the b.e.c.'s at the third and second inflexions of the titration curve of hydrogen mica were as 3 : 1 was at once found to follow

from the idealized formula $H^*Al_2(AlSi_3)O_{10}(OH)_2$ of hydrogen mica, assuming that for each H^+ ion (marked with an asterisk in the formula) of the above category, the two OH groups which are structurally identical react with the base through hexagonal rings of oxygens at the third or final inflexion. The portion of the titration curve between the second and third inflexions therefore corresponded to the neutralization of H^+ ions dissociated from these OH groups. In view of the undoubted similarity between muscovite and illite indicated by their powder diagrams and chemical compositions, the parallel features of the titration curve of hydrogen illite admit of a similar explanation. In other words, the second inflexion in the titration curve of hydrogen illite indicates H^+ ions balancing the (negative) 'isomorphous charge' of the crystals, and the third inflexion gives a measure of their available OH groups. The significance of the first (weak) inflexion is, however, not so clear. It will be remembered that this inflexion is not shown by the KOH-curve. The fact that it is seen when titration with this base is done in the presence of a salt might be fortuitous as it might be due to Al^{+3} ions mobilized by the salt. The titration curve of the sol+KCl mixture does show its initial buffering and the first inflexion in the range of pH where a soluble aluminium salt would be expected to show similar features (Britton, 1942). The clear supernatant liquid above the coagulum of the sol+salt mixture was actually found to contain some Al^{+3} ions. The fact remains, however, that titration with $Ba(OH)_2$, potentiometric and conductometric, shows the first inflexion quite clearly and it is extremely unlikely that, in the absence of a salt, this inflexion would be caused by Al^{+3} ions. In the case of hydrogen mica, the first inflexion was observed on titration with all strong bases, including KOH; moreover, there, the titration curve often[1] started from a pH as high as 5·8 which is well above the upper limit of the range of pH within which aluminium hydroxide is precipitated, thus ruling out the possibility of the initial buffering of the titration curve and its first inflexion being due to Al^{+3} ions. Taking all these into consideration, the first inflexion in the titration curve of hydrogen illite with $Ba(OH)_2$ does appear to indicate H^+ ions on the surface. Assuming this to be the case, the first inflexion appears to differentiate between H^+ ions balancing the isomorphous charge of the illite crystals and allocates them between two sub-levels of affinity on the surface. H^+ ions at the flake edges and corners would no doubt have bonding energies different from those located on the flake surfaces proper.

Base-exchange Capacity of Illite

The value (about 60 m.e. per 100 g.) of the base-exchange capacity of illite given by the third inflexion in the titration curve is much higher than that (20 to 40 m.e. per 100 g.) reported for this mineral based on analytical determinations of the b.e.c. by some routine methods. These methods depend on estimating the amount of cations taken up by a clay from solutions of salts. The ill-defined character of the b.e.c. as

[1] When dilute suspensions were used.

measured in this manner and the part played by the pH of the contact solution and adsorption of cations from it have been discussed elsewhere (Mitra, 1942). The various routine methods give rise to different pH's of the contact solution and, in particular, different cationic environments for the H^+ ions on the surface, and this is the reason why they do not give identical results. The higher the equilibrium pH and the greater the equilibrium concentration as well as the valency of the exchanging cation, the larger will be the amount of H^+ ions which will be exchanged. However, in no case an analytical method should give a value of the b.e.c. which will be greater than that indicated by the final inflexion in the titration curve of the fully desaturated or hydrogen form of the clay. The following results obtained with hydrogen illite bear out these conclusions.

TABLE I

Base-exchange Capacity of Hydrogen Illite obtained by Different Methods

Method of estimation	*pH at which b.e.c. is measured*	*B.e.c. in m.e. per 100 g.*
1. Potentiometric titration with KOH . .	7·6 (second inflexion)	20·0
	11·0 (final inflexion)	60·0
2. Parker's method (estimation of Ba taken up from N $Ba(Ac)_2$)	7·0	42·0
3. Ba taken up on leaching with N $Ba(SCN)_2$.	7·2	44·0
4. Ba taken up on leaching with $8·5N$ $Ba(SCN)_2$	8·5	58·0

Parker's method (Parker, 1929) and leaching with N $Ba(SCN)_2$ give a higher value of the b.e.c. than the titration curve at its second inflexion, though the pH, in each case, is lower than that at the second inflexion. The strong 'absorbability' of the Ba^{++} ions present at the high concentration of $1·0N$ makes it possible for them to replace some of the hydroxylic hydrogens in addition to the H^+ ions which balance the isomorphous charge and are indicated by the second inflexion in titrations without addition of salts. At the much higher concentration, $8·5N$, of the saturated $Ba(SCN)_2$ solution and at the higher pH of 8·5, the combined pH and cation effect is sufficiently strong to effect a complete replacement of all available H^+ ions on the surface, isomorphous as well as hydroxylic.

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THE pH OF NATURAL SOILS AND ITS ECOLOGICAL SIGNIFICANCE

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Introduction

In attempting to summarize the ecological aspects of pH in natural soils it is necessary to start by emphasizing the danger of generalization. The limitations of evidence must also be appreciated. These limitations arise partly from the use of the ecological method, which must necessarily attempt in the first place to establish correlations between the distribution of plants and the habitat factor studied. It will be necessary therefore to consider the assumptions made in both in reference to plant distribution and to measurement of soil pH.

From the present point of view it is also necessary to define 'natural soils' as those existing under native types of vegetation. The existence of correlations between native vegetation, climate, and soil type is commonly assumed by pedologists and thus it may perhaps be pardonable for the ecologist to regard the nature of a well-established vegetation cover as one biological manifestation of soil properties. It is clear that there should be some emphasis on the term *well established*, for if there were reason to suspect that either soil or vegetation cover were in a state of active transition, significant correlations might not exist.

It has proved more convenient to use widespread units of clearly defined and well-established types of vegetation than to study the distribution of single species. Measurements of soil pH in relation to the distribution of individuals of a single species show that many plants exhibit wide limits of tolerance of soil pH or, putting it in another way, the presence or absence of isolated individuals of a single species may have little or no significance.

It is equally necessary to make sure that measurements of soil pH are comparable. Unless otherwise stated, the soil pH will here be taken as that at 10–15 cm. below the surface, the measurements made in 1:2 soil:water suspensions with the glass electrode. Some care is necessary to avoid possible drifts in pH and in other soil properties associated with microbiological changes in the soil on disturbance or transportation to the laboratory.

Soil Trends

As stated above, in considering possible correlations between vegetation types and soil pH we should only consider cases in which it is believed that the soil and vegetation cover were in a steady state with no probability of recent disturbance. The term 'steady state' rather than equilibrium is used deliberately because there is clear evidence that natural soils in Britain are subject to soil trends, due especially to leaching

with resultant acidification and to other forms of deterioration. These trends have been associated with the replacement of woodland by heath and bog types of vegetation, a point of view that has been developed at some length elsewhere (Pearsall, 1950). It may be of interest to recall here that the first demonstration of the rate of leaching in natural soils by Salisbury (1925) showed that 250 years or so sufficed for almost all the calcium carbonate in sand-dunes to be removed by leaching so that

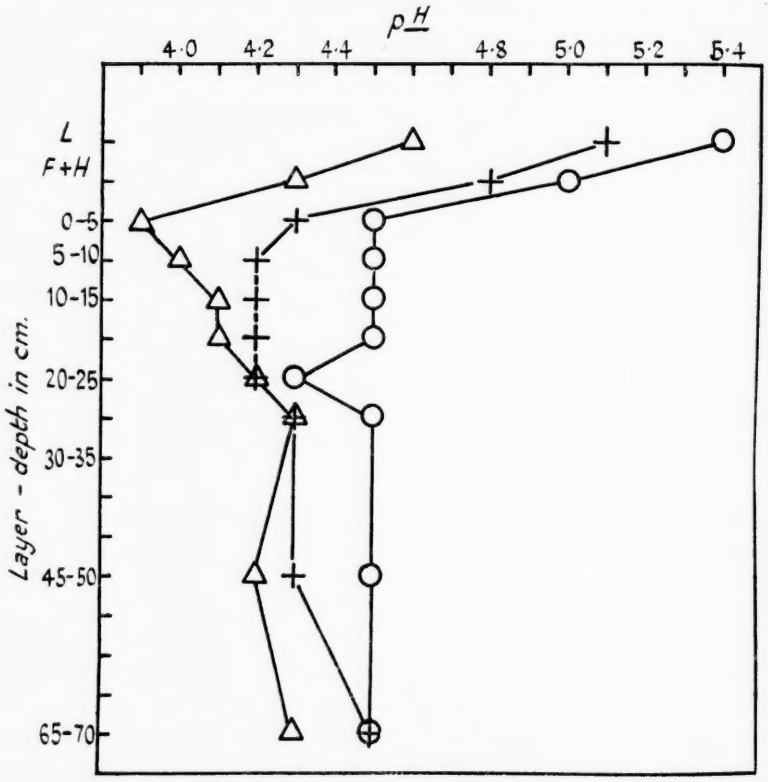

FIG. 1. Change of pH profiles in woodland soils associated with replanting. Symbols: (+) the original oak-wood with hazel-chestnut coppice and the same 20 years after replanting with (△) *Picea omorika* or (○) *Quercus rubra*. (Data of J. D. Ovington.)

the soil pH fell from 7·8 to 5·0. In heavier soils under natural woodland vegetation, changes due to leaching may be much slower. Nevertheless, measurable accelerations due to long-existing changes in vegetation can be detected. Thus in an area of oak woodland on the Chilterns pH values (at 15 cm.) of 4·79, 4·60, and 4·54 were obtained, while in one block of the same wood which had been planted with chestnut (*Castanea sativa*) for about 70 years the corresponding pH values were 4·28, 4·09,

and 4·02 and there were associated differences in texture, colour, and base-saturation. J. D. Ovington, in unpublished work, has developed this type of inquiry very thoroughly, showing clear correlations between the pH profiles developed in woodland soils and the type or species of tree planted thereon. In the example from his results given in Fig. 1, the original condition of the soil profile under mixed woodland with oak standards and hazel-chestnut coppice is represented by the middle broken line. Most of the area investigated had been cleared 20 years previously and replanted in plots containing one species of tree. The pH profiles under the diverse trees differ in the manner shown in the figure for two of them, *Picea omorika* and *Quercus rubra*. The differences appear to be statistically significant and they show that, even in a comparatively short time, the character of the vegetation affects the soil pH and the pH profile. There is thus clear evidence that we are dealing with dynamic systems.

Significant Limits of pH

The ecologist can usefully recognize certain limits of pH which can be correlated both with certain types of vegetation and also with other soil properties. Among well-established communities of woodland plants there appear to be obvious boundaries about soil pH values near 3·8–4·0 and 4·8–5·0 (Pearsall, 1938). The plants regarded as *calcicole* usually occur on soils above pH 6·5, in contrast to well-defined communities such as heather-moor, or dense woodland communities of bilberry, *Vaccinium myrtillus*, or the grass, *Deschampsia flexuosa*, which are characteristic of soils below pH 3·8. Well-established communities of soft grass (*Holcus mollis*), bluebell (*Scilla*), and of wood millet (*Milium effusum*) are found only above this limit. The commonest type of oak-wood with bracken, bluebell, and soft-grass ground-flora is characteristic of soils in the range pH 3·8–5·0. Communities of the wood brome (*Brachypodium sylvaticum*) and such plants as garlic (*Allium ursinum*) and dog's mercury (*Mercurialis perennis*) are characteristic of still higher soil pH values (above about 4·8). Many young trees show similar preferences for soils above certain limits. Only pine and birch are commonly found below pH 3·8.

These general limits, while not necessarily or always very sharp, acquire more significance if we consider other soil properties such as the relation between the base-exchange characters of a natural soil and its hydrogen-ion concentration. An ecologist may usefully think of four main phases in the soil trend—from neutral to highly acid. Above about pH 6·5 are 'base-saturated' soils with perhaps a 'calcareous' sub-class containing free calcium carbonate. A second class consists of a type familiar to agriculturists, i.e. 'lime-deficient' soils between pH 6·0 and about pH 5. Still more acid soils may be called perhaps 'base-deficient', lying between about pH 4·8 and 3·8, in which iron is becoming mobilized, but is still present as a principal base. The most acid class we can call 'hydrogen' soils, below about pH 3·8 or so. These names are, of course, only generalizations which may serve to focus attention on noteworthy

features of the base status. It will be realized also that characteristic features of the soil profile commonly accompany these surface changes.

In natural soils the base-exchange properties are often predominantly those of the humus fraction. These limits of pH are useful because they serve also to define types of humus, particularly in terms of certain biological attributes of the soil humus that can be fitted into the same limits of pH. In Britain we can distinguish on biological grounds three types of humus in woodland soils:

1. *Mull* (on the more nearly base-saturated soils above pH 4·8–5·0).
2. *Mor* (on hydrogen soils below pH 3·8).
3. Transitional soils between these limits.

The field ways of distinguishing *mull* are by the presence of animals such as the larger earthworms, moles, and snails (which occur in the 'calcareous' range), by the presence of nitrates *in the field*, and by certain elements of the fungus and bacterial flora.

It is becoming clear, however, as has been emphasized by L. G. Romell (1932), that *mor* differs not only in the usual absence of such elements but also in its different *metabolism*—starting with a different animal population, e.g. worms, and passing on to a different fungal and bacterial flora and shown by a different mode of nitrogen utilization.

The most noticeable feature of British *mor* soils is the normal absence of nitrates (by field tests). This is not to say that they are not at times absent in more normal soils. They may be absent in spring wherever their utilization is rapid. Moreover, they are also normally absent in anaerobic soils. In *mor*, the characteristic absence of nitrate is due not to oxygen deficiency (Romell, 1935; Pearsall, 1938), but to a rate of formation so low as to be negligible under field conditions. There is reason to believe that nitrate-forming organisms are present in at least some types of *mor*, for when disturbed (e.g. by cultivation or digging) rapid nitrate formation may take place. Nevertheless, the negligible amounts of nitrate present in nature point to a real difference in metabolism that is apparently associated with the lower rate of conversion of the nitrogenous compounds in *mor* soils.

D. J. Boatman (unpublished work in this laboratory) has developed a simple method which can be used to show a difference in the nitrogen metabolism. A nutrient solution containing an amino-acid (alanine, for example) is inoculated (in the field if need be) with a small volume of fresh soil. After inoculation it is observed that *mull* soils (above pH 5) rapidly give a measurable production of ammonia at a constant logarithmic rate while *mor* soils (below pH 3·8) only produce it after a marked delay and then only at a slower rate. This suggests that there are both quantitative and also qualitative differences in the condition of the soil micro-organisms that utilize amino-acids as well as of those that liberate ammonia. Methods involving the output of CO_2 have not, however, proved useful in distinguishing *mors* from *mulls*.

The trend towards lower soil pH which is associated with the development of these qualitative differences in the soil humus is also associated with an increase in the soil organic content (see Fig. 2). There develops

a marked tendency for humus to accumulate in the surface layers rather than to be distributed more uniformly throughout the upper metre of soil. As is shown in Fig. 2, the rise in humus content is marked in the region below pH 5 where transitional humus types occur. It is in this

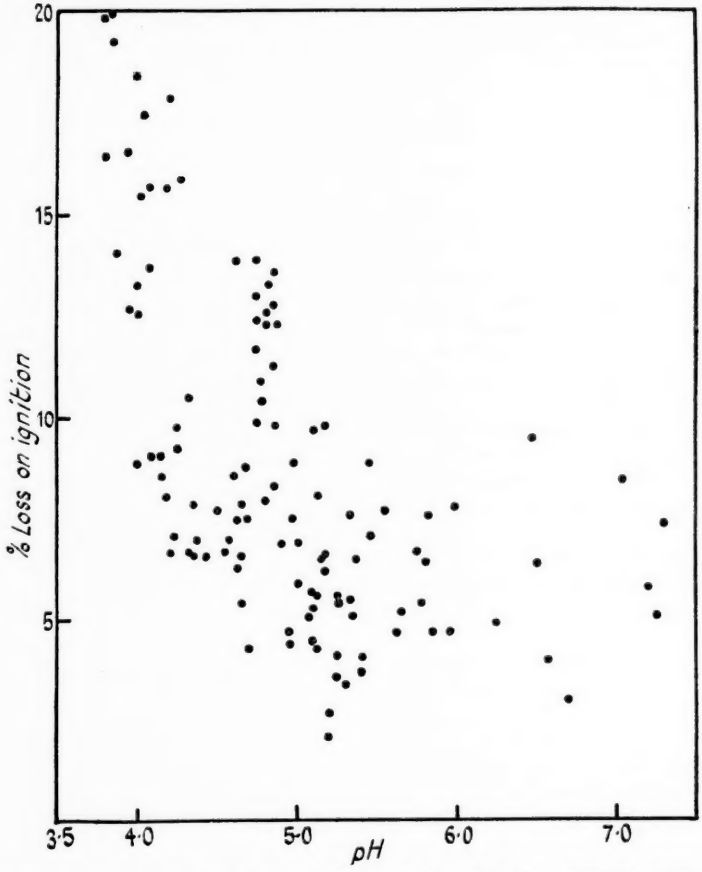

FIG. 2. Ignition losses in relation to pH for soils from Whippendell Wood, Herts. (Data of G. S. Puri.)

pH range that the character of the soil humus is most sensitive to effects produced by changes in the vegetation. Generally speaking the C/N ratio of the humus tends to rise as the soil pH falls, and below pH 3·8 it is usually above 20.

Peats

The accumulation of soil organic matter in this way leads ultimately to peat formation. The frequency with which surface peat is formed,

particularly in the north and west of Britain, is evidence of a widespread soil trend towards peat formation on base-deficient soils as a marked feature of the damper climates in Britain. The study of these peaty soils has suffered from a good deal of confusion of thought. There is no necessary connexion between 'wet' and 'acid' as is often implied. On the contrary it must be emphasized that oxidation (as a result of a lower humidity) is a necessary precursor of high acidity in peaty soils. From the ecological point of view the following evidence may be quoted in illustration of this fact.

Wetness is a seasonal phenomenon in most British soils. There are a few soils, it is true, that are permanently water-logged and, as a result, anaerobic and permanently reducing in character. Most wet soils are in this condition only in winter; in summer they are drier and are effectively and biologically oxidizing, even if the rate of oxygen penetration is small. We can take the view that other things (such as the availability of bases) being equal, the acidity of these peaty soils depends mainly on the intensity and duration of the oxidizing phase.

In soils such as lake muds and developing peat bogs where there is a reasonable probability that the organic matter has always been under anaerobic or reducing conditions, no pH value below 5·4 has yet been observed. R. D. Misra (1938) obtained this result after examining 95 soils of this type from waters of low mineral-salt content. Many more samples examined since have only confirmed this conclusion.

In peat-bogs developing from small peaty pools or tarns, greater acidity develops when the peat surface rises high enough to dry out partly in summer. The pH value then shows a negative correlation with the intensity and duration of summer drying and oxidation. The results summarized in Table 1 illustrate this succession of events.

TABLE 1

Development of Vegetation in Order of Age and of Peat pH in August 1948 around a Peaty Lake

Vegetation	*pH range*	*E*	*Water/Humus*
1. *Carex inflata* with *Menyanthes* or *Equisetum limosum* (6)	5·51±0·2	165±20	17—14
2. *Sphagnum*-bog with *Molinia* and *Myrica* (6)	5·40±0·25	175±25	13—10
3. The same—older (8)	4·69±0·30	250±60	
4. *Sphagnum—Erica tetralix—Narthecium* (5)	3·93±0·20	300±100	10—7
5. Originally as last, but drained 4 years before (4) *Molinia—Betula*	3·70—3·45	595—500	6—4

E is redox potential in mV. No. 4 was oxidizing and No. 5 strongly oxidizing at the time of the observations.

A similar correlation, though necessarily vague and possibly open to other explanations, has been traced between the typical pH value of peats from certain 'raised bogs' and the rainfall of the regions in which they occur (Pearsall, 1938). Here again the most acid peats are those

from the drier climatic conditions, that is, from the places where the summer oxidation period is most prolonged, as is illustrated by Table 2.

TABLE 2

pH of Central Parts of Little Altered Peat-mosses compared with Rainfall (R) of the District in cm. per Annum

District	*pH range*	*R*
Connemara . . .	5·46–4·66	250–230
Galway . . .	4·45–4·30	120–110
Central Ireland . .	4·10–3·86	95–85
Solway . . .	3·70–3·40	80–60

Finally, the most acid peats are found to be the driest under natural conditions. Thus pH values below 3 may occur, and these are generally associated with such plants as bilberry (*Vaccinium myrtillus*) and with water/humus ratios well below 2 in summer. Some of the lowest soil pH values recorded for natural peaty soils in Britain are from the peaty layers of dry heaths (Haines, 1926).

The effects of drying and oxidation on the pH of peat can, of course, be demonstrated in other ways. In samples of bog-peat brought into the laboratory and allowed to dry slowly in air, very large changes of pH have been recorded. Thus the acidity (1:2 soil:water sampling) of Connemara bog peats treated in this way changed from pH values of 5·46 and 4·72 to as little as 3·25 and 3·27 respectively (Pearsall and Lind, 1941).

In large blocks of peat treated in this way, Mr. A. C. S. Wright and the writer measured the pH directly with a glass electrode placed in permanent holes in the centre of the block. The pH changes on drying were as follows:

	pH at start	*pH after 20 days*
(*a*) Base-deficient willow-carr peat . . .	5·6	4·6
(*b*) Regenerating *Sphagnum*-bog . . .	4·9	4·0
(*c*) Raised-bog *Sphagnum*-peat . . .	4·3	3·7
(*d*) Amorphous oxidized peat of type (*c*) . .	3·8	3·0

There is the interesting point here that peat of type (*d*) which was unquestionably once in the same condition as (*c*) has now a permanently lower pH range as the result of drainage and oxidation. This is an irreversible change which must be distinguished from the reversible changes which can be produced by drying and reflooding, as shown in Fig. 3, which refers to a similar experiment in which the peat blocks were reflooded with water after partial drying.

The changes of pH measured directly (i.e. without the addition of water) could be partly at least due to direct concentration effects on drying. Similar effects, however, can be demonstrated in 1:2 soil: water suspensions so that there must be an additional production of

acid. This is not extractable in aqueous solution, and hence must be associated with the humus colloids.

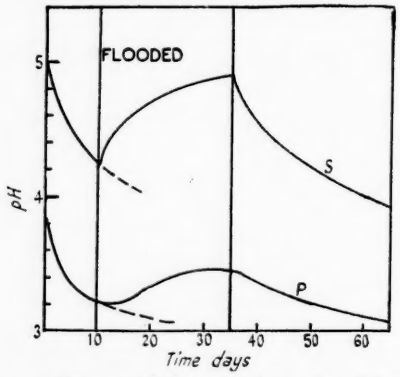

FIG. 3. Changes of pH on drying peats, *S* from a regenerating *Sphagnum*-bog, *P* from similar peat, highly oxidized in nature and under pines.

Generalization

It will be seen that, taking a wide view of what has been said, an integrated view of natural soils as a whole involves the assumption of relations like those expressed in Fig. 4 in which the very wet soils with a narrow pH range change, as the average or summer water content gets less, to the more normal and oxidized types of soil with a wide pH

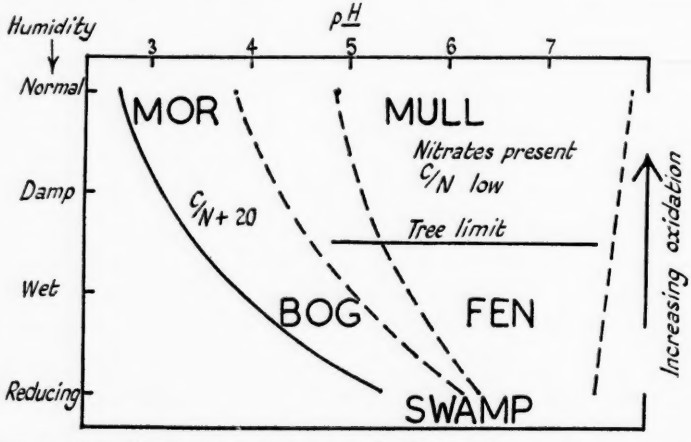

FIG. 4. Generalized relations between soil pH, humidity, and humus types.

range. Although such a generalized scheme is very useful for thinking purposes it is certainly much too simple. The vertical scale in such a

scheme must always involve more than differences of humidity, or even of oxidation, for water always carries dissolved bases—not only if it is telluric in origin but also even if it derives mainly from rain. Moreover, seasonal differences in duration of oxidation or waterlogging cannot be expressed on such a generalized scheme.

Seasonal Changes

Seasonal rhythms of pH in natural soils have been described, but not completely accounted for. It is often possible to detect a pattern which would be expected as a result of drying and oxidation in summer and flooding in winter. Thus pH values tend to fall in late summer or autumn, and may be highest in spring. But it is probably rare to find that the seasonal drifts exhibit only these expected changes, and this difficulty is shown in the data recorded for acid bog-peats (Conway, 1949) and for woodland soils (Clapham and Baker, 1939).

A common and recognizable difficulty is that the high winter water content is the result of seepage from an adjacent soil which may be as a rule more oxidized or less oxidized than the one examined. Thus the pH of the seepage water may be lower or higher as the case may be.

Moreover, in general, heavy rain must introduce a phase when the soil and water have not yet reached an equilibrium or a steady state.

Finally, in wet soils the effects of changing from an oxidizing to a reducing state must also involve pH changes whose magnitude is as yet inadequately known. In cases examined (Pearsall, 1950*a*; Mortimer, 1941) the reducing condition is associated particularly with the appearance of Fe and Mn in reduced form (of lower valency and higher solubility) and also with a somewhat higher pH.

Metabolism

One other point is worth comment. Just as the 'metabolism' of the normal dry soil changes at some level of pH to give the very acid *mor* soils, so similar changes ensue in very wet soils. It is interesting to ask if a pH boundary between the two types exists and, if so, where it should be drawn. The best examples for studying this effect are probably to be found in lake muds where constant conditions of humidity exist. One such example, shown in Fig. 5, deals with reedswamp peats in which the 'metabolic' effect is shown at quite a high pH. The parent organic material is here derived from reeds and is rich in carbon. Nevertheless, the C/N ratio of the humus in sites of high pH (i.e. receiving a sufficiency of bases) is nearly as low (10–12) as in good terrestrial soil. When base-supply becomes low and the pH falls below about 5·7, a strong tendency is observed for the C/N ratio to rise, as is shown in the figure. This can only mean that the micro-organisms in these peats either act in a different way (e.g. liberating nitrogen more readily, which appears unlikely) or else act more slowly so that unmodified vegetable matter accumulates. The indications are that the latter is the correct explanation and that Fig. 5 is comparable with Fig. 2 for terrestrial soils.

The examples considered in the preceding pages illustrate the fact that the pH value of natural soils in Britain is related to at least four other soil properties, namely: (1) base status, (2) water content, (3) soil metabolism, (4) vegetation. Because of these correlations, and if their

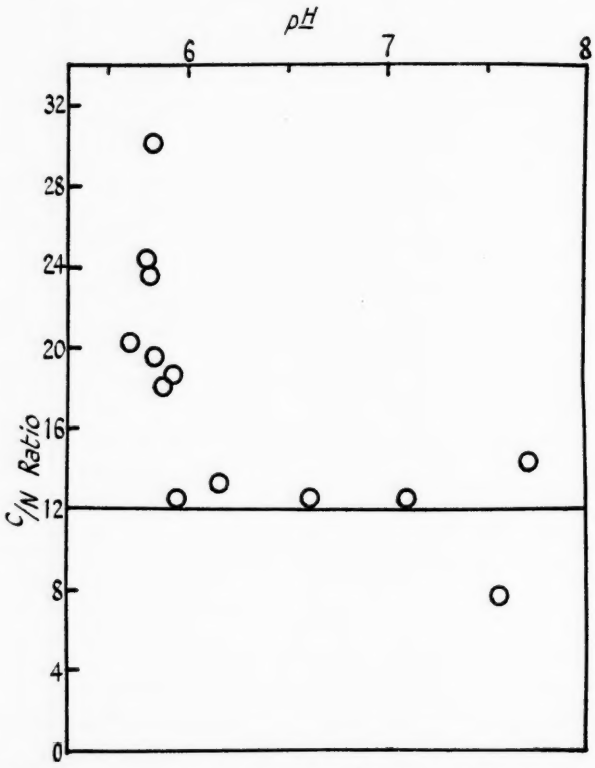

FIG. 5. Carbon-nitrogen ratios in reed swamp peats of diverse pH values.

existence is appreciated, it may safely be said that the soil pH remains as the most useful single measurement that can be made for ecological purposes.

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GENESIS OF A TROPICAL RED SOIL

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THE red clays to the north of Salisbury, S. Rhodesia, are deep residual soils, derived from an olivine-dolerite sill. Similar soils occur throughout the country.

The site selected for sampling was on the Agricultural Experiment Station, Salisbury. Many years ago the indigenous trees, *Brachystegia spiciformis* and *Isoberlinia globiflora*, which occur naturally as open savannah, were stumped out. The land was cultivated for one season and put down to pasture.

The site is at an altitude of 4,900 ft. with an average annual rainfall of 30–35 in. confined very largely to the summer season, falling between November and March. The rainfall is heavy, falls of 1 and 2 in. being quite common. The rains are preceded by two normally dry, extremely hot months, and are followed by a short autumn passing to a dry, cold winter, in which, however, the day temperatures may be quite high (see Table 8). From a soil-forming point of view the rainy season is a period of intense chemical and biological activity, whereas during the dry season such activity is brought almost to a standstill. During the 2 months preceding the rains there is probably some slight upward movement of the products of weathering.

The pit was sunk to a depth of 20 ft., down practically to hard parent rock. It was dug during the dry season. The ground in the vicinity was level with a very slight slope to the west. About half a mile north-north-east is a low hill of dolerite, with numerous exposed boulders. Some alluvial material from this area may have been deposited in the vicinity in the past, but the soil is considered to be very largely residual.

Pit Description

Lab. No.	*Depth*	
488/R/37	19–20′	Decomposing rock, grey-green in colour, running into hard, solid, but not unbroken dolerite at 20 ft. Very damp.
489/R/37	18–19′	Same as the lowest horizon but with small particles of brown decomposing rock among the grey-green. Soft and very damp.
490/R/37	17–18′	More uniform green-brown colour. The brown colour which resembles weathering iron begins to appear and increases as the profile rises. Black patches (presumably iron ore) are also frequent. Soft and damp.
491/R/37	16–17′	Similar to 490/R/37. At 17 ft. there is an occlusion (or an inclusion) of clay. Covered with heavy black powdery staining.
492/R/37	15–16′	Browner and drier with gritty fragments. Small pockets of clay more and more frequent.
493/R/37	14–15′	Browner with clay inclusions. At 14 ft. there is a moist layer of decomposing rock with clay.

494/R/37	13–14′	Heavy chocolate-brown clay mixed with decomposing rock in an advanced stage of decomposition and full of black stainings.
495/R/37	12–13′	Lighter in colour and in texture with light brown decomposing rock: stainings frequent. Moist.
496/R/37	11–12′	Reddish-brown almost completely decomposed rock with layer heavier clay. Stainings frequent. Moist.
497/R/37	10–11′	Slightly mottled in appearance: iron stainings and reddish mottling as of the last stages of decomposing rocks. Moist.
498/R/37	9–10′	From 9 ft. to 9 ft. 6 in. brown with black iron stainings: below 9 ft. 6 in. the faint red mottling begins. Moist.
499/R/37	8–9′	Brown and loamy with stainings and dark iron-manganese concretions. Moist.
500/R/37	7–8′	Brown and loamy with a few small pebbles of rock. Areas in this layer are of extraordinary fineness and friability and are thought to be the last stages of weathered rock. Other areas are clayey. Stainings and concretions numerous. Moist.
501/R/37	6–7′	Brown moist loamy soil with stainings and concretions. Rather pebbly and in parts almost stoney.
502/R/37	4′ 9″–6′	Brown rather pebbly in feel, the pebbles being largely hard compacted soil stained with iron and manganese. Less moist.
503/R/37	4′ 6″–4′ 9″	A layer of dry hard compacted soil fragments and pebbles, with faces stained with iron and manganese. Varying in width from 3 to 6 in. and even 9 in. in places. Forms a wavy line around the whole pit.
504/R/37	3′ 6″–4′ 6″	Fine-grained friable soil with numerous roots. Drier than horizons below 503/R/37.
423/R/37	2′ 6″–3′ 6″	Red, fine grained, very friable to crumbly with roots. Slightly moist, no stainings or concretions. Roots numerous.
422/R/37	1′ 3″–2′ 1″	Red, fairly friable, slightly more compacted. Roots numerous. Very slightly moist.
421/R/37	6″–1′ 3″	Reddish-brown, rather hard and compacted. Less crumb structure than top soil from which there is a marked change. Numerous roots. Scarcely moist.
420/R/37	0–6″	Brownish-red, dry, fairly compacted, but with excellent crumb structure. Roots very numerous.

On the surface, particularly of bare soil after rain, there is a dusting of black shiny metallic-looking grains, an analysis of which is given. It is largely titaniferous magnetic iron oxide. It is not apparent in the horizons on ordinary profile examination except at the base of pockets of clay, but during mechanical analysis it was found to occur in the sand fractions of all layers and it occurs in the parent rock.

Under the microscope the roughly spherical concretions with brown staining on the outside are blackish and seem to have been deposited in layers. The centre has a dark black slag-like appearance, but towards the outside, faint brownish tinges appear.

The profile dried out rapidly and readily down to the layer of clay gravel at 4 ft. 6 in., with an irregular fracture. The lower layers dried out more slowly with fairly large, mainly vertical cracks. The clay-gravel horizon appeared to be the limit of normal drying.

The influence of old root channels in modifying the nature of the deeper soil is marked. Soil in their vicinity is finer and more friable, due no doubt to the effects of organic matter, aeration, and bacterial action.

The pockets of clay in decomposing rock are difficult to account for: they may constitute the ends of old root channels (the *Brachystegia* and the *Isoberlinia* being deep rooting) or may be merely some phenomenon of local weathering.

Review of Profile

Looking from the surface downwards, decomposing rock first begins to make a faint appearance at about 9–10 ft. as a pale reddish rare mottling in the brown. At 10 ft. this becomes a reddish-yellow colour which merges at between 12 and 13 ft. with the more or less continuous yellow-grey-green decomposing rock. The weathering naturally is less marked with depth and the yellowish-grey-green merges imperceptibly into a grey-green which continues into the almost unweathered rock. Between 9 and 10 ft. seems to be the limit of soil formation.

From 13 ft. downwards there does not appear to be any black iron-manganese staining (except in the clay pockets), although the purple augite of the rock as well as its iron ore make observation difficult in the decomposing rock. The titaniferous iron-ore fragments occur in all horizons, but cannot readily be seen unless concentrated.

The round black soft concretions occur from about 5 ft. to 9 ft., together with small, often rounded pieces of undecomposed rock and irregular pebbly fragments of consolidated soil (originally thought to be clay), stained purplish black in parts. Some of the black stainings scraped off the consolidated soil pebbles were magnetic. Some few soft concretions and small pebbles of rock occur very isolated in the upper horizons, but they are not a feature of the profile as they are between 5 and 9 ft. Where found they are much smaller than in the lower horizons.

A curious feature of the profile is the zone from 3 up to 9 in. thick of hard, dry, compacted soil with smooth fractures and dark stainings on the surface of the fractures. This zone is not at constant depth around the pit but may vary from 3 ft. 9 in. to 4 ft. 6 in. In places it is almost continuous; in others the pieces are discrete. Where apparently continuous it fractures readily into hard pieces, irregular in shape, from half an inch to an inch long. Even when the rest of the profile, or a similar profile which was exposed nearby, was damp, these fragments were comparatively dry and hard.

The top 6 in. of soil represent the zone of eluviation of clay: the zone of illuviation is from 6 in. to about 2 ft. with a maximum in the region of 1 ft. 6 in. From 2 ft. 6 in. to the zone of compacted soil gravel the soil is completely free of stainings and concretions and is very crumbly and open in texture, but below that zone it tends to get slightly more compacted.

Geology

The actual description of the rock (taken a few yards from the present pit at a depth of 24 ft.) as given by Maufe (1928) is as follows:

In the hand specimen the dolerite is even-grained, medium textured, and mottled black and white, the augite and felspar crystals being readily distinguishable.

Under the microscope olivine, biotite, and an iron ore are found to be primary constituents occurring in amounts much smaller than the abundant felspar and augite, whilst hornblende, serpentine, and dusty iron ore occur in very small amounts as alteration products of the primary constituents. The felspar is labradorite.

Analyses

The results of analysis of material passing the 2-mm. sieve are shown in the following tables, together with analyses of the rock and of various samples of soil given by Maufe.

Clay analysis was carried out according to Van Tongeren (1937).

Exchangeable bases were determined by the method of Rice Williams (1929). So-called exchangeable manganese was determined on this acetic-acid extract. Mechanical analysis was done by the method of Bouyoucos (1934) as modified in these laboratories. The analyses were commenced many years ago. The true clay, as defined in the international method, is that figure shown in the tables as 'fine clay'.

Available manganese and manganese dioxide were determined by the method of Piper (1931).

The clay fraction was separated by stirring, in the Bouyoucos stirrer, 100 g. of soil with water and 2 c.c. of concentrated ammonia. After standing 18 hours the clay was siphoned off at a depth of 10 cm.

TABLE 1

Analyses of Clay Fractions

Lab. No.	*Depth*	SiO_2 %	Fe_2O_3 %	TiO_2 %	Al_2O_3 %	*Silica/ Alumina (Molecular)*	Mn (*mg. per 100 g.*)
420	0–6″	34·86	18·43	0·83	28·78	2·055	121·6
421	6″–1′ 3″	35·66	18·48	0·78	30·26	2·000	121·0
422	1′ 3″–2′ 1″	36·29	18·10	0·70	31·40	1·961	115·5
423	2′ 6″–3′ 6″	36·24	17·86	0·66	30·88	1·991	126·5
503	4′ 6″–4′ 9″	35·56	17·99	0·57	30·10	2·004	116·9
502	4′ 9″–6′	35·78	18·54	0·58	30·20	2·010	125·1
500	7–8′	36·04	18·61	0·55	29·86	2·047	122·4
498	9–10′	36·34	19·38	0·58	28·72	2·146	158·1
496	11–12′	37·36	19·89	0·59	27·16	2·338	..
494	13–14′	38·18	18·22	..	27·98	2·319	192·5
493	14–15′	40·12	18·64	0·50	26·20	2·603	180·1
492	15–16′	42·44	16·37	0·73	21·54	3·350	121·0
490	17–18′	43·10	17·19	..	22·38	3·274	127·9
488	19–20′	42·96	15·59	0·61	18·16	4·022	..

Results and Discussion

The weathering as disclosed by the clay analysis follows the pattern generally assumed for tropical soils, that is the removal of silica and the consequent enriching of the clay in iron and alumina. The SiO_2 content drops from 47·66 per cent. in the fresh rock to 42·96 per cent. in the clay of the decomposing rock to 34·86 per cent. in that of the top soil. This loss is probably considerably less than is generally assumed for such soils under subtropical conditions.

TABLE 2

(Very full analyses of all samples were carried out. The most significant figures are summarized below.)

Lab. No.	*Depth*	*Features*	$\frac{SiO_2}{R_2O_3}$	*Clay* %	*Exch. bases m.e./100g.*	*pH*	*Water-sol. salts* %	N %
420	0–6″	Roots	1·458	48	10·9	6·1	0·03	0·16
421	6″–1′ 3″	,,	1·438	62	6·7	5·8	0·02	0·10
423	2′ 6″–3′ 6″	,,	1·454	53	5·4	6·0	0·01	0·03
503	4′ 6″–4′ 9″	Dry, pebbly	1·451	48	5·0	5·3	0·01	..
502	4′ 9″–6′	Mn cons.	1·444	49	5·3	5·6	0·01	..
500	7–8′	,, ,,	1·465	47	5·6	5·6	0·01	..
499	8–9′	,, ,,	..	47	6·1	5·8	0·01	..
498	9–10′	Faint mottled	1·500	45	6·6	5·7	0·01	..
497	10–11′	Mottled	..	39	8·6	5·7	0·02	..
496	11–12′	Mottled	1·593	32	11·7	6·4	0·02	..
495	12–13′	Getting	..	28	13·2	6·5	0·06	..
494	13–14′	lighter in	1·638	29	11·7	5·9	0·03	..
493	14–15′	colour and	1·790	16	11·9	6·2	0·05	..
492	15–16′	denser, less	2·255	10	11·3	6·4	0·06	..
490	17–18′	weathered	2·196	10	13·6	7·2	0·08	..
488	19–20′	Decomposing rock	2·597	9	14·1	6·8	0·04	..

Horizontal bars indicate horizons in which maximum changes appear to take place.

These results confirm that the zone of greatest change is in the vicinity of 10 ft. Observations in the pit had indicated, by faint mottling and slight differences in texture, that weathered rock changed to soil-like material at about 10 ft. The greatest change in the silica-sesquioxide ratio of the weathering rock is at much greater depth. It appears likely therefore that the chemical changes in most of the rock minerals have been carried to completion long before the weathered rock finally passes to true soil. From a depth of 12 ft. to the surface there is virtually no change in the silica-sesquioxide ratio of the clay fraction. The only conclusion seems to be that once the rock has fully weathered the nature of the clay is very little affected by climate and vegetation. The pH is virtually constant from just below the A horizon to 12 ft., as is the content of total exchangeable bases except for a slight rise, to be expected, in the B horizons.

The decrease of the total exchangeable bases from the rock to the surface, in spite of an increasing content of clay, is partly a function (though only slightly) of the unsaturation which develops, but is more particularly a measure of the increasing kaolinization of the clay, which appears to be completed with the transition from weathering rock to soil.

This soil is similar to the 'red earth' derived from andesite in Grenada and described by Hardy and Rodriques (1939). They state: 'The red earth proper may thus be regarded as a *zone of completed secondary changes*.' The formation of primary laterite as a crust on the weathering rock found in Grenada is not a feature of Rhodesian soils.

TABLE 3

Estimation (extraction with Magnet) of Magnetic Iron Oxide in Coarse-sand Fraction

Lab. No.	420	421	422	423
Iron oxide, % of Coarse Sand	11·14	5·91	6·79	9·91

TABLE 4

Analyses of Circular Black Concretions and of Surface Magnetic Iron Oxide

(Expressed in percentages)

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	Fe_3O_4	MnO_2
Concretion . . .	23·53	17·77	0·75	21·09	..	36·22
Surface oxide . .	1·84	1·64	12·42	..	82·99	..

TABLE 5

Analyses of Fresh Rock, Decomposed Rock, Red Subsoil, and Red Top Soil from an Olivine-Dolerite Sill, Salisbury (Maufe, 1928)

(Expressed in percentages)

	Fresh rock	*Decomposed rock*	*Red subsoil*	*Red top soil*
Depth	..	17–24′	1′ 7″–17′	0–1′ 7″
SiO_2	47·66	43·82	40·94	42·50
Al_2O_3	15·28	23·28	27·23	25·22
Fe_2O_3	1·02	16·65	17·92	16·91
FeO	8·01	..	..	..
MgO	9·62	2·94	0·50	0·93
CaO	13·74	2·70	0·23	0·18
Na_2O	1·86	0·76	0·10	0·09
K_2O	0·55	0·21	0·17	0·19
TiO_2	0·67	1·41	1·63	1·87
P_2O_5	0·12	0·06	0·05	0·03
MnO	0·14	0·20	0·18	0·27
BaO	0·04	..	..	..
SrO	0·05	..	..	..
FeS_2	0·28	..	..	..
Loss on ignition . .	..	8·43	11·89	11·89

The enrichment of the clay in alumina is gradual and continual to the upper horizons and is at a maximum in the horizon 1 ft. 3 in.–2 ft. 1 in., which is the zone of maximum illuviation.

The behaviour of the iron is more variable. The iron content shows a sudden sharp increase from the parent rock to the weathering material, particularly when it is remembered that according to Maufe a large part of the iron ore of the original rock remains unweathered to the surface. It is thereafter at its maximum in the zone 11 ft.–12 ft. where there is a sudden sharp rise in the pH. It then declines to the zone 2 ft. 6 in.–3 ft. 6 in. and then rises again.

The analysis figures of the whole soil (Table 7) in the upper horizons do not show any significant trend. The greater content of silica, and the lower content of iron and alumina in the top 6 in. as compared with the zone 6 in.–1 ft. 3 in. may be largely attributed to the higher concentration of sand fractions in the top 6 in.

It would appear that the greatest loss of bases occurs at the first stage of weathering when the hard rock first begins to undergo decomposition.

TABLE 6

Manganese

Lab. No.		*Exchangeable manganese m.e./100 g. (See Table 2)*	*Available manganese m.e./100 g.*	*Manganese dioxide m.e./100 g.*
488		0·15	0·88	6·21
489		0·15	0·79	6·40
490		0·16	0·81	8·53
491		0·17	0·72	9·95
492		0·11	0·62	7·88
493		0·16	0·71	8·68
494		0·28	1·10	9·65
495		0·26	0·92	8·72
496		0·32	0·96	10·22
497		0·30	1·03	8·43
498		0·48	1·20	8·56
499	Concretions not included	0·56	..	..
500		0·48	0·86	3·86
501		0·44	..	..
502		0·61	0·82	3·74
503		0·65	1·22	4·10
504		0·80	..	..
423		1·01	1·77	5·12
422		1·10	..	..
421		1·75	3·28	5·60
420		2·55	5·60	7·10

Total manganese in the soil was not determined.

TABLE 7

Fusion Analysis of Soil

(Expressed in percentages)

Lab. No.	*Depth*	SiO_2	Fe_2O_3	Al_2O_3	TiO_2
421	6″–1′ 3″	40·80	16·53	27·48	1·66
420	0–6″	45·64	15·24	22·38	2·94

An idea of the genesis of the soil, the different stages of its development over a long period of time, may be obtained by studying the profile from the bottom to the top, although such factors as the influence of organic matter and aeration cannot in this way be properly visualized. The true soil may be presumed to have passed through all the stages disclosed in the profile from the hard rock to the surface: each stage of development in the profile, to put it another way, represents a chapter in the history of the soil, although the changes near the surface would have been more rapid.

The first stage is the breakdown of the parent rock by carbonation and hydration and in this process, from a soil-forming point of view, the decomposition of the abundant felspars is the most important reaction. Labradorite consists of albite and anorthite in proportions varying from one of albite and one of anorthite to one of albite and three of anorthite.

TABLE 8

Climatological Summary (over a period of 10 years)

(Figures supplied by the Director, Meteorological Office, S. Rhodesia)

	July	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*Year*
Mean maximum temperature, °F. .	69·6	73·5	79·3	82·7	80·9	79·0	77·7	77·7	77·6	77·3	73·8	69·7	76·6
Mean minimum temperature, °F. .	43·8	46·7	52·2	57·9	59·4	59·8	60·3	60·1	57·8	54·4	48·3	44·6	53·8
Mean temperature, °F. . . .	56·7	60·1	65·8	70·3	70·2	69·4	69·0	68·9	67·7	65·9	61·1	57·2	65·2
Mean relative humidity, % . .	57	52	46	47	58	68	74	76	72	67	58	58	..
Rainfall (inches) (average of 30 years) .	0·03	0·10	0·20	1·15	4·02	7·10	7·71	6·89	4·70	1·07	0·33	0·09	33·44

The chemical reactions taken to completion may be presumed to be as follows:

Albite: $Na_2Al_2Si_6O_{16} + CO_2 + 2H_2O = H_2Al_2Si_2O_8H_2O + Na_2CO_3 + 4SiO_2$

Anorthite: $CaOAl_2O_32SiO_2 + CO_2 + 2H_2O = H_2Al_2Si_2O_8H_2O + CaCO_3$.

The end product in each case is kaolinite, together with an alkaline or alkaline-earth carbonate, and in the case of albite, silica as well.

Augite, $n[CaO(Mg_2FeO)2SiO_2] + n[Mg,Fe(O)(Al, Fe)_2O_3SiO_2]$, and hornblende give rise to calcium and magnesium carbonates, to calcium and magnesium metasilicates—which are possibly the reserve minerals of these elements in the soil—and to compounds of Fe, Al, and Mg. Some of the free iron which is released is oxidized to hematite, Fe_2O_3. It is this substance which coats the particles of soil, and imparts to the whole soil its characteristic reddish-brown colour. Free aluminium oxides and hydroxides are also formed.

If the profile truly represents the various stages in the genesis of the soil then the carbonates of sodium, potassium, calcium, and magnesium are very transient in the soil. There was no trace in the profile of carbonates in the weathering rock, and only very small amounts on the surface of the hard rock. It is necessary to visualize the weathering from the beginning, when what is now the profile was solid rock or boulders. The immediate products of chemical action, as the surface began to weather, were alkaline carbonates which were rapidly lost in the run-off water. There was no possibility of the accumulation of calcium and magnesium carbonates in a lower horizon because below the weathering surface was hard rock.

So the process continued, down through the rock, with no possibility at any time, because of the good drainage, of excessively alkaline weathering. On the surface some ferrous salts oxidized rapidly to hematite which was hydrated to form limonite. The titaniferous magnetite remained largely unweathered. As the soil deepened and the aeration of the percolating water lessened, the processes of oxidation and hydration diminished, though not nearly to the same extent as in humid temperate climates, because of the dry season, terminating in 2 months of high temperatures, which caused the soil to dry out and to crack. During the drying out some soluble salts must have been brought up by capillarity: the maximum concentration of soluble salts—0·083 per cent. —was found in the decomposing rock at a depth of 18–19 ft. This raising of soluble salts, which contributed to some slight extent to the weathering and to the saturating of the exchange complex with bases, could only have occurred while the soil was relatively shallow—it is thought that 4 ft. 6 in. represents the limit of drying out—but owing to the diminution in the percolating water these soluble salts would have remained longer in contact with the weathering clay at depth. Gradually, however, with the growth of plants and the leaching of bases, the soil became acid, and a certain amount of mobilization of the sesquioxides and a considerable mobilization of manganese occurred.

There are two features in the profile that present some difficulty in interpretation. These are the zone of hard nut-like fragments of stained

compacted soil at 4 ft. 6 in. and the zone of soft black manganese concretions mainly between 5 ft. and 9 ft. When these concretions were first examined it was thought that they represented old calcareous nodules around which soluble manganese had precipitated. From an examination of the profile, however, in conjunction with the results of analyses, it is obvious firstly that no such nodules are likely to have formed, and secondly (Table 4) that silica and alumina, as well as iron and manganese, would have to be carried in solution in order to give the composition of the concretions as found. It seems much more likely that the concretions form around particles of weathering rock. For some reason small particles of rock—usually rounded in the case of dolerite—have not completely weathered and occur scattered throughout the profile. As they weather they give rise to Ca, Na, K, and Mg carbonates and it is on these carbonates that iron and manganese, mobilized higher up in the profile and carried down in solution, are precipitated. Because the movement is seasonal the deposition is in layers. The figures in Table 6 would seem to indicate that most of the MnO_2, in the horizons in which concretions occur, is concentrated in the concretions.

The layer of compacted soil at 4 ft. 6 in. was thought to be due to one of several causes. The most attractive theory was that it represented clay, made acid and deflocculated by the action of soil roots and carried down to the depth of drying out which coincides fairly closely with the depth of the grass roots. The Mn removed during the process of acidifying in the presence of organic matter would have accounted for the manganese concretions. But the mechanical analysis shows this material to have a texture in conformity with the soil immediately above and below it. It is not clay. It has also a texture closely resembling that of the top 6 in., except that the silt is higher and the coarse sand lower. It is therefore possible that after the period of drying out the onset of the rains washes some of the top soil down the numerous cracks to the depth of drying out. With the alternate wetting and drying, and the resultant expansion and contraction, this material might be consolidated into the hard nut-like material found. With the water movement in the presence of the organic matter carried down, and the lack of replenishment with bases (which the top soil continually receives), this layer has become depleted in bases and sufficiently acid to mobilize the manganese and iron, which are carried to the lower levels and deposited. This is the most likely explanation. The third theory, that the layer might represent a thin belt of more resistant rock, does not fit all the observed facts.

Conclusions

Under conditions of free drainage it is not possible to see how weathering can proceed in the manner stated for sub-tropical and tropical soils by many writers. It is very frequently stated that under these conditions basic weathering proceeds to a point where the silica is removed to such an extent that the soil becomes lateritic. The exact mechanism of the basic weathering is never precisely stated, but it would seem, at least under Rhodesian conditions, that the basic weathering is a function of the basic constituents of the felspars and is strictly limited. When the

felspars contain much K, as in orthoclase, or Na, as in albite, four parts of silica are removed and two parts remain in the clay complex. When the felspars contain calcium as in anorthite, no silica is removed in the process of carbonation. If the soluble products of weathering—the carbonates—are not removed, in areas of poor drainage, the reaction cannot proceed normally, and under these basic conditions there should be less loss of silica and not more. This is the case in the half-bog black soils of the dolerite catena, where according to analyses in this laboratory the silica content of the clays is much higher and the iron and alumina contents lower than in the corresponding red soil. These soils are alkaline, pH 7–8, and contain carbonate nodules.

Although this is in no sense a treatise on laterite it might be as well to add that under Rhodesian conditions the formation of laterite is never a residual process brought about by the removal of silica. It is a secondary process due to the mobilization of iron, manganese, and to a less extent alumina, and their reprecipitation in a lower horizons. It occurs frequently in soils derived from a mixture of basic and acid materials, as, for example, dolerite and granite, or from rocks particularly rich in iron, such as banded ironstone. It occurs in regions of considerable leaching (with a resultant acid reaction in the upper horizons) and some temporary waterlogging during the rains. Under these conditions, particularly when there is organic matter present, manganese is mobilized, some Fe is reduced to soluble ferrous compounds, and a little alumina is also dissolved. These are carried down into the lower horizons, but because of the poor drainage, are not entirely leached away. When the soil dries out during the dry season they are precipitated as insoluble compounds, or they may tend to precipitate round focal points of neutrality or slight alkalinity such as exist originally in the lower horizons. Eventually there are formed the diffuse lateritic pebbles which are a feature of the lower horizons of many Rhodesian soils.

The iron, manganese, and aluminium which do drain away in solution move down to the lower lying wet areas. In those parts which remain wet throughout the year there is no laterite, but very intensive gleying. Towards the edges of the vleis, however, or in certain spots, where there is a high water-table during the rains but complete drying out during the dry season, the soluble iron and manganese, and to a less extent the aluminium, are precipitated and oxidized to insoluble compounds. The end product of this process is solid laterite, the typical 'bog-iron ore'.

In effect it may be said that the podzolization which tends to develop under Rhodesian conditions once the upper soil is fully formed and has become acid may, under certain conditions, lead to the formation of laterite.

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THE DISTRIBUTION OF ORGANIC MATTER IN DEPTH IN SOME TROPICAL SEASONALLY FLOODED SOILS

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IT is the purpose of this paper to describe the distribution in depth of organic matter in a number of tropical Sudan soils. Two of these are recent alluvia and a third is seasonally flooded soil from the Upper Nile Province. They all have the unusual feature of having considerable variations with depth in content of organic matter as contrasted with the gradual decrease associated with soils of temperate regions.

I. *Darfur Seasonally Flooded Soil*

The most striking topographical feature of Darfur is the Marra mountain range, rising 9,000 ft. above the surrounding country. It is of volcanic origin, and from it and other smaller hills of basement-complex rocks the seasonal streams carry soil material and water to the alluvial flood-plains round the mountain. The soils of these flood-plains are among the most fertile in the Sudan. During the rains and by flooding they are soaked with water to great depths, crops are sown after the floods subside and thereafter receive no important amount of rain. The two most important crops grown on these areas are sorghum and tobacco. Of this last the species *Nicotiana rustica* is grown and used inside the Sudan, mainly for snuff making.

The various deposits forming these soils lie upon one another in discrete layers, and the different texture of these layers and their corresponding changes in moisture-holding capacity are paralleled by changes in content of organic matter. The following abbreviated profile description illustrates these points. The hole was in the Wadi Azum, a wide watercourse near Zalingei on the west side of the mountain.

TABLE I

Zalingei Alluvium (*Lat. 12° 54′ N., Long. 23° 29′ E.*)

Depth (*in.*)	*S.G.* %	*C.S.* %	*F.S.* %	*Silt* %	*Clay* %	*Exch.* Ca. *m.e./100 g.*	C %	N %
0–7	0	20	52	9	19	17	4·16	0·24
7–9	0	3	43	19	34	22	4·93	0·31
9–15	0	73	23	1	2	1	0·15	0·02

The total nitrogen is by Kjeldahl, carbon by a slightly modified Walkley-Black method using 0·75 as factor. The size ranges for the mechanical analysis figures are the usual ones based on coarse sand fraction 2·0 mm. to 0·2 mm.

The middle layer of the profile was much darker in colour than the two others. This highly developed organic profile was quite common in the Wadi Azum.

On the east of the mountains profiles were examined at Shingletobai in a tobacco-growing area. Again the site was seasonally flooded. The following table gives the mechanical analysis for two holes.

TABLE 2

Shingletobai Alluvium (*Lat. 12° 57′ N., Long. 25° 12′ E.*)

PROFILE 1

Depth (in.)	*S.G.* %	*C.S.* %	*F.S.* %	*Silt* %	*Clay* %	*Salts* %	*pH*	P_2O_5 *p.p.m.*	N %
0–8	0	7	48	12	33	0·10	7·95	1,000	0·107
8–21	0	77	15	2	6	0·03	8·30	390	0·023
21–36	0	8	49	13	31	0·03	8·50	850	0·048
36–40	0	80	17	1	3	0·09	8·55	160	0·013
40–50	0	6	34	27	33	0·05	8·30	1,200	0·028
50–52	0	33	57	4	6	0·02	8·65	400	0·016
52–64	0	7	35	26	32	0·05	8·20	1,000	0.048

PROFILE 2

Depth (in.)	*S.G.* %	*C.S.* %	*F.S.* %	*Silt* %	*Clay* %	*Salts* %	*pH*	P_2O_5 *p.p.m.*	N %
0–6	0	16	45	13	27	0·09	8·00	430	0·056
6–11	0	65	27	2	6	0·02	8·55	320	0·011
11–20	0	19	41	12	28	0·08	8·30	920	0·051
20–25	0	10	50	16	24	0·07	8·65	920	0·035
25–31	0	1	46	19	34	0·14	8·20	920	0·055
31–40	0	10	56	11	23	0·07	n.d.	920	0·042
40–52	0	8	36	16	40	0·12	8·15	920	0·056
52–64	0	4	25	12	60	0·05	8·45	1,200	0·028

The texture variations in the various layers of these two profiles are paralleled by changes in organic-nitrogen content. This completely obscures the decrease of organic matter with depth usually exhibited by soils. At the time of sampling the water-table was much lower than the depth of the holes. The distribution of organic matter was not therefore influenced by a water-table within reach of the roots. It will be noticed that in Profile 1 the nitrogen percentage in the 52–64 in. layer is the same as in the 21–36 in. layer; while in Profile 2 the 40–52 in. layer contains as high percentage of nitrogen as does the surface layer itself.

The mechanical-analysis figures in the table do not show that in fact all the coarse sand is smaller than 1 mm. The favourable moisture relationships of these Shingletobai soils is shown by their being able to mature a tobacco crop without either rain or irrigation, relying only on stored water.

The phosphate figures are by Truog's method. They are of course extremely high figures. During a general study of Darfur Soils it was found that phosphate figures of this order are only found in the Marra Mountains and in soils directly derived from them. The salts are measured conductimetrically.

II. *Soils of Tokar Delta*

The Tokar Delta is an important cotton-growing area. Situated on the Red Sea coastal plain, it receives the water of the River Baraka which rises in the hills of Eritrea. On reaching the coastal plain the river ceases to have any defined channel and the seasonal stream spreads over the delta and seldom or never reaches the sea. The area flooded varies largely from year to year. Land sufficiently well flooded is sown with Egyptian-type cotton, and after sowing usually receives only a little further water from light and irregular rains. The average rainfall at Tokar is 85 mm. (1913–40).

The soils of this alluvial area though variable are fertile except for some areas near the sea that are influenced by saline ground water. The average yield of seed cotton is 660 lb. per acre (1941–50). The soils show the same kind of changes of organic matter with depth as do the seasonally flooded soils of Darfur.

TABLE 3

Tokar Alluvium (*Lat. 18° 26′ N., Long. 37° 44′ E.*)

PROFILE 1

Depth (*in.*)	*S.G.* %	*C.S.* %	*F.S.* %	*Silt* %	*Clay* %	*Salts* %	*pH*	C %	N %
0–7	0	0	29	18	53	0·05	8·10	1·27	0·105
7–16	0	2	46	17	35	0·03	8·50	0·25	0·025
16–21	0	0	16	31	53	0·07	8·40	0·45	0·055
21–34	0	4	38	18	40	0·04	8·70	0·23	0·017
34–38	0	0	16	46	38	0·07	8·40	0·38	0·045
38–47	0	1	22	20	57	0·09	8·45	0·56	0·064
47–55	0	0	33	33	34	0·14	8·25	0·37	0·041

PROFILE 2

Depth (*in.*)	*S.G.* %	*C.S.* %	*F.S.* %	*Silt* %	*Clay* %	*Salts* %	*pH*	C %	N %
0–6	0	0	18	29	53	0·78	8·05	0·79	0·060
6–12	0	0	44	29	27	0·38	8·10	0·36	0·034
12–18	0	0	70	16	14	0·21	8·40	0·12	0·017
18–24	0	0	40	43	17	0·45	8·20	0·20	0·020
24–30	0	0	24	46	30	0·65	8·15	0·48	0·030
30–36	0	0	12	45	43	0·80	8·10	0·60	0·064
36–42	0	0	7	37	56	0·73	8·15	0·64	0·066
42–48	0	0	23	28	50	0·74	7·90	0·47	0·053
48–54	0	2	41	30	27	0·72	8·05	0·33	0·025

Rejecting only the surface step of Profile 1 the correlation coefficient for percentage nitrogen against percentage of clay in the remaining 15 steps of the two profiles is +0·851, which is highly significant.

Profile 2 was on a site not flooded in the year of sampling. The vegetation at both sites was mainly nut grass (*Cyperus rotundus*). In both cases the roots of these plants could easily be traced to 3 ft. Profile 2 was sited towards the seaward side of the delta and has a much higher

salt content than the other. It will be noticed that this hole was sampled in 6-in. steps—the absence of observable layering in the soils of the delta near the sea is a regular feature which may be due to the soils there being older than the more western soils at the apex of the delta. It is interesting that the much larger salt contents of this profile have not influenced the nitrogen-texture relationship.

III. *White Nile Riverain Soils*

The soils described are from the region of Bor (6°12′ N., 31°33′ E.) and are all subject to heavy flooding either by the river or rain water. The two groups of soils previously described are both alkaline; the regularly flooded riverain soils of Bor are acid soils, with iron-stained profiles and impeded drainage. The rainfall at Bor is much heavier than in Darfur and the Tokar delta. The water relations of these soils are often complicated by the presence of ground water near the surface. They do, however, show the same changes of organic matter with texture as the alluvial soils of Tokar and Darfur.

TABLE 4

Malek (*Lat. 6° 04′ N., Long. 31° 36′ E.*)

Depth (*in.*)	*S.G.* %	*C.S.* %	*F.S.* %	*Silt* %	*Clay* %	*Salts* %	*pH*	N *p.p.m.*
0–6	0	1	49	11	39	0·08	5·50	1,570
6–12	0	1	54	8	36	0·05	6·05	770
12–18	0	1	39	9	51	0·04	5·95	760
18–24	0	0	27	12	60	0·07	6·05	1,000
24–30	0	0	23	12	65	0·05	6·10	910

Ajak Bior (*Lat. 6° 09′ N., Long. 31° 33′ E.*)

Depth (*in.*)	*S.G.* %	*C.S.* %	*F.S.* %	*Silt* %	*Clay* %	*Salts* %	*pH*	N *p.p.m.*
0–6	0	0	40	8	52	0·11	6·40	2,600
6–12	0	0	38	15	47	0·10	6·35	530
12–18	0	0	28	11	61	0·09	6·35	690
18–24	0	0	29	13	58	0·09	6·10	590
24–30	0	0	24	13	63	0·13	6·20	520
30–36	0	0	17	15	68	0·12	5·85	450
36–42	0	0	15	11	75	0·14	5·70	770
42–48	0	0	9	9	83	0·16	5·85	1,142

In the Malek hole the water-table was at 3 ft. at the time of sampling. The vegetation at both sites was *Echinocloa pyramidalis*, a typical grass of flooded soils in this region.

The dependence of nitrogen on texture is by no means so close in these soils as in the samples from Darfur and Tokar.

Discussion

Most organic-matter profiles described in the literature show a continuous decrease with depth, the rate of decrease varying widely with the nature of the soils. The only soils in which the organic matter does not decrease continuously with depth are the podzols. The cause of the accumulation of organic matter in the B horizon of podzols is its downward translocation from above. In the case of the soils described in this paper it is suggested that the discontinuities in organic matter in the profiles are due mainly to varying root development in horizons of different texture. In each case the upper soil is subjected to extreme desiccation and the vegetation must obtain the bulk of its water supply from the lower layers of the soil. It appears that the horizons of finer texture provide a more favourable material for root development than do those of coarser texture. If this explanation is correct it seems likely that the same mechanism could operate in temperate climates. Since an accumulation of organic matter in a horizon is likely in itself to make the horizon a more favourable medium for root growth, the process once started would tend to maintain itself. It is therefore possible that accumulation of organic matter in the B horizon of podzols may be partly maintained by increased living-root development in the horizon as well as by additions from above. The accumulation of clay in the podzol B horizon might also contribute to increased root development there, particularly in sandy profiles.

Summary

Three alluvial soils from widely separated parts of the Anglo-Egyptian Sudan are described, all showing changes of organic matter with depth which are closely related to texture changes. It is suggested that the reason is better root development in layers of more favourable soil moisture relationships. The phenomenon may occur in a less well marked way in temperate region soils. In some tropical alluvial soils its occurrence may have a value in soil assessment.

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THE SOILS OF SYRIA AND THE LEBANON[1]

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WITH TWO PLATES

1. *Topography and Geology*

LEBANON and Syria are bordered on the west by the Mediterranean, on the south by Israel, Jordan, and the Jordanian Desert, on the north by the foothills of the Taurus Mountains, and on the east by the Syrian Desert and the Euphrates and Tigris valleys connecting Syria with Mesopotamia.

A series of mountain chains stretching from south to north with a slight north-east inclination divides the coast from the rest of the country. These mountain chains (the Lebanon and the Ansariye Mountains) provide for a west–east passage at various gaps only, such as the stream-beds of the Nahr el Kebir and the Orontes.

The littoral and the Jezireh, mostly covered by rich alluvial soils, receive sufficient rainfall for agricultural purposes. These regions, the littoral (with its southward Israeli prolongation), the Jezireh, and Mesopotamia, form a crescent and are therefore often referred to as the 'fertile crescent', embracing the desert regions of the interior.

To the east, the mountain chain is divided from the Hauran, the Antilebanon, and the vast expanse of the Syrian Desert by a deep depression, the Bekaa and its northern continuation the Ghab.

We can therefore distinguish between the following topographic features:

1. The littoral on the Mediterranean Sea.
2. The western mountain chain (the Lebanon and Ansariye Mountains).
3. The depressions of the Bekaa and Ghab.
4. The eastern mountains (the volcanic plateau of the Hauran, the Hermon, and Antilebanon).
5. The piedmont plateau of the Kurdish Mountains (Jezireh).
6. The Syrian Desert.

Minor topographic features are the flood-plains of the Euphrates and various smaller rivers as well as the well-irrigated alluvial plain of Damascus.

[1] The material for this paper was collected before and especially during the war, when the author was serving with the British Forces. It had been the aim of the author to study these soils still further, but the Israel-Arab war and the inaccessibility of the University Laboratories on Mt. Scopus have prevented this intention. This also explains the absence of many important analytical data such as base exchange, &c. The author is especially indebted to the excellent work accomplished by the pioneer of Syrian Geology, Mr. L. Dubertret.

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A short description of these main topographic features follows.

a. The littoral. The Phoenician coast, between Tyre and Beyrouth, is much narrower than its Israeli counterpart, the mountains rising abruptly a short distance from the sea. This is why the Phoenicians, limited by a narrow strip of soil, looked towards the Mediterranean. The hinterland presents an almost impassable barrier. However, the steep mountain slopes had been well terraced in antiquity. The northern part of the coastal plain with the harbours of Tripoli and Lattaqie is likewise narrow. A larger alluvial plain exists at the outlet of the Nahr Kebir which is known as the plain of Akkar. A few river valleys such as the Nahr el Kebir (Eleutherus) and the Orontes provide access to the hinterland. The fertility of the alluvial plains of the littoral and the abundance of water have given rise to irrigated agriculture since remote antiquity.

There are no major dune-sand accumulations except near Tyre and Tripoli.

b. The western mountain ranges. Mt. Lebanon, with peaks rising to over 3,000 metres, consists mainly of Jurassic and Cretaceous limestones, sandstones, and clays. Where these clays come to the surface they give rise to copious springs. Much of the Lebanon is Karst-land with typical lapiez formations (Plate I). The northern continuation of Mt. Lebanon, the Ansariye Mountains, are basaltic on their southern boundaries, but for the most part consist of limestones and marls with some basaltic cones. Chalky marls occupy many of the lower-lying plateaux of Mt. Lebanon and the Ansariye Mountains. These layers are impermeable to water and only where weathering has caused cracks and fissures can water penetrate to a certain extent. The water entering these cracks can be reached by wells which need only penetrate a depth of about 15 metres.

The foothills of the Antitaurus, north of Mt. Ansariye, comprise volcanic 'green rocks' such as pyroxenolites, peridotites, and serpentines. Some metamorphic rocks, gabbros, and diorites also occur in this region. Forests of Aleppo pine grow on these rocks which weather into an almost lime-free soil.

c. The depressions of the Bekaa and the Ghab. A broken-down strip of a north-to-south fault of Mt. Ansariye is occupied by the marshland of the Ghab depression, comprising an area of 100,000 acres. The bad drainage of the Ghab is due to a lava flow which almost completely bars the outlet of the Orontes river. At one point a shallow passage only has been worn through this impediment. In antiquity the conditions of this fever-ridden district were apparently different. Farther south the Orontes has cut a tortuous way before reaching the basaltic plain of Homs.

The Bekaa depression starts from Lake Homs southward, separating Mt. Lebanon from the Antilebanon. South of Baalbek the valley is covered by rich alluvial terra rossa. The southern prolongation of both depressions is the deep rift valley of the Jordan.

d. The eastern mountain ranges. The Jaulan (bordering Lake Tiberias) and the Hauran (ancient Bashan) plateaux form a fertile table-land with rich volcanic soil and were once one of the granaries of the Roman

Empire. The nearby Druze Mountains contain recent volcanic cones which rise to a height of about 2,000 metres. To the north-west and north-east of the Druze Mountains stretches the inhospitable and barren lava-covered area of the Leja. The Jaulan rises gently in a north-westerly direction to the slopes of Mt. Hermon, which consists of basalt at its foot and of hard Jurassic limestone higher up. Its snow-covered top rises to over 3,000 metres. Mt. Hermon and the Antilebanon form another barrier to transport from the sea coast and dominate the eastern side of the Bekaa. The Antilebanon, with peaks rising to approximately 2,800 metres, consists mainly of Cenomanian limestone, whereas the lower ridges are formed by conglomerates and chalky marls. To the east of the Antilebanon lies the Damascus oasis, its alluvial soil being watered by the Barada river and its canals.

e. The Jezireh. To the east of Aleppo, along the Turkish border, lie the foothills of the Kurdish Mountains and the rich alluvial lands of the Jezireh. This region forms the top arc of the 'fertile crescent' and through this 'Syrian saddle', a wide open and well-watered steppe-land, caravans and armies have crossed since ancient times.

The Jezireh (i.e. the island between the Euphrates and Tigris) affords areas for grazing and the growing of cereals. The Jezireh is well watered by rivers and springs, the most important rivers being the Euphrates, the Balikh, the Khabbour, and the Jagh-Jagh draining the country in a north-to-south direction. This now scantily cultivated region, without facilities for irrigation, had been an export centre for cotton and a region of olive culture in antiquity. The slightly undulating steppe is covered by chalky marls of Miocene age and of alluvial deposits. Dubertret's 1933, 1943, 1944 maps show basalt as occurring west and east of Hassetche as well as being predominant in the 'Duck's Bill', the eastern extension of the Jezireh, where the frontiers of Turkey, Iraq, and Syria meet. The author has found, however, that wide stretches, especially west of the Balikh river, are likewise basaltic. Many of the 'tells' rising above the plain are, in fact, extinguished volcanoes (e.g. Tel Banndar, Tell Hajeb, &c.). There are more outcrops of basalt, apparently unobserved hitherto, in the limestone country south of Ain el Arab (Arab Pounar) and approximately 7 miles east of Ras el Ain.

f. The desert. South of an imaginary line drawn from Aleppo to Hassetche rainfall diminishes and the steppe turns into desert. This Syrian desert, which has an immense expanse, is a slightly undulating table-land (100–300 metres high). It is mainly built up by chalky marls which give rise to a calcareous, sometimes gipseous, yellowish-brown loam. Vast stretches of this desert loam alternate with gravelly patches.

Such 'Hammada' areas result from physical weathering, the rock, mostly flint, disintegrating into innumerable gravelly fragments. Wind-blown sand occurs at many places, Palmyra amongst others. Ridges and hills are buried under their own debris, the latter accumulating due to the lack of water run-off. None of the many wadis crossing the desert have a perennial flow; they often cause bad drainage in winter and subsequently the formation of salt swamps (*sabkha*). After the winter

rains the soil sustains a coarse vegetation serving as a grazing-ground for camel and sheep. Occasionally slightly salty springs are found, and it is at such places that caravan cities such as Palmyra were built. A special feature of the Syrian desert are the ruins of ancient huge storage reservoirs, dams, and the underground water supply furnished by *foggaras*. Secondary deposits of calcium carbonate and silica often form impervious layers in the underground of the permeable marly formations. The water-bearing strata thus formed were exploited by the Romans in an ingenious way. Deep shafts (often 30 or more metres deep) were dug out of the ground at short distances in order to tap the trickles of water at the base of the layers. These shafts were interconnected by a tunnelled channel which had just sufficient slope to lead the water off. Such chains of shafts often extended for many miles in the desert, collecting bits of water from hundreds of shafts until a small underground stream was created. These *foggaras* are marked at regular intervals by circular heaps of rubble from the dug-out earth. This made cultivation possible far out in the desert and some *foggaras* yielding several gallons of water per second are still in use, as at Jaroud, east of Damascus (Plates I and II).

A network of canals from the Euphrates and other rivers made irrigation possible in ancient times. Since these canals are not cared for any more they have become silted up and once fertile regions have been turned into desert. Along most of its course the Euphrates as well as the other Syrian rivers are accompanied by riverine vegetation only.

2. *Climate and Vegetation*

Whereas the climate of the Lebanon is typically Mediterranean, the climate of Syria is Mediterranean only near the sea and at high altitudes. Farther inland rainfall diminishes and the climate becomes arid. Characteristic for the whole region, however, is the occurrence of a well-marked season of winter rains alternating with a completely dry period in summer. Precipitation in the winter months may rise to a total of well over 1,000 mm. in the mountains, accompanied by heavy snowfall, or may be less than 100 mm. in the desert. Approximately 5 months in summer are completely dry (Combier, 1933, 1945).

As pointed out elsewhere by the author (1947*a*), Lang's method of calculating the 'rain factor' (the quotient obtained by dividing the rainfall by the temperature) has been of great value in rapidly summarizing the climatic and soil-formative conditions of the Mediterranean region. Admittedly, false conclusions would be arrived at by the usual method of calculation, for the processes of chemical weathering which start in winter are brought almost to a complete standstill in summer. We therefore make use of the data for the winter months only when calculating the rain factor; the physical disintegration of the rock is of much smaller pedological importance than weathering by hydrolysis. Taking the winter season as 7 months (October–April), we obtain climatic data for a number of localities as shown in the following table. If we compare the rain factors with the soil map we see that, on the whole, the rain

factors correspond broadly with quite definite soil types. (Cf. also Fisher (1950), where, unfortunately, the calculated figures are not correct.)

TABLE 1

Rain Factors for Some Localities in Lebanon and Syria during Winter (October–April)

Climate	*Locality*	*Elevation (m.)*	*Rainfall (mm.)*	*Temperature (°C.)*	*Rain factor*
Arid	Palmyra	443	109	16	7
	Deir ez Zor	213	140	13	11
	Damascus	755	191	12	16
Semi-arid	Jerablus	390	242	11	22
	Hassetche	315	289	13	22
	Homs	541	323	12	27
	Kamichlieh	520	324	12	27
	Selemiyeh	475	344	12	29
	Suweida	920	337	12	28
Semi-humid	Aleppo	437	456	11	41
	Beyrouth	40	840	18	47
	Lattaqie	..	820	17	48
Humid	Ksara	1,010	581	10	58
	El Kareya	1,100	1,310	10	131

We may therefore distinguish between an arid desert zone (rainfall below 200 mm., rain factor below 20), a semi-arid steppe zone (rainfall between 200 and 400 mm., rain factor between 20 and 30), and a semi-humid Mediterranean zone (rainfall between 400 and approx. 800 mm., rain factor between 30 and 50). It will be seen from the table that at very high altitudes the rain factor may be far above 50, but it has not yet been possible to differentiate between these 'humid' areas and the semi-humid zone as far as soil types are concerned. It is maintained (Muir, 1951) that brown forest and podzolized soils are found here. It seems to the author that even in these high altitudes it is the dryness of summer which primarily influences soil formation and that the soils are not much different from those in the semi-humid zone.

Vegetation in the treeless *desert zone* consists mainly of shrubs and sub-shrubs such as *Artemisia herba alba*, *Salsola rigida*, *Haloxylon articulatum*, &c., and it is only after the winter rains that a shortlived flora of annuals develops (Zohary, 1940). In the salt swamps (*sabkhas*) we find halophytic plant associations.

It is only along the banks of the Euphrates that a riverine vegetation consisting of the Euphrates poplar in association with willows and tamarisks is found. In the *steppe-region* we meet with scattered trees of terebinths as well as a great variety of shrubs and sub-shrubs (buckthorn, sumach, lotus, artemisia, &c.). The *Mediterranean zone* is characterized by typical maqui, and in the mountainous districts small areas of

forest consisting of pines, oaks, firs, and isolated groves of cedars are found. Many wild flowers, especially in the coastal plain, cover wide areas in spring. It seems that the higher parts of Djebel Druz form a Mediterranean enclave within the steppe region. The resulting soils have still to be studied.

Vegetation has adapted itself to the aridity of the summer months, many plants completing their life cycle within the rainy period. The roots penetrate deep into the soil in order to obtain a maximum of water. Thick and hard leaves diminish the transpiration. The hot and dry south-eastern and eastern winds (*khamsin*) are detrimental to the vegetation. The heavy night dew, on the other hand, helps plant growth to a certain extent in summer.

The countries of the Levant had a much richer vegetation in ancient times. Wide areas were once covered by woods. The present scarcity of trees and the denuded character of the country-side are not to be ascribed to a change in climate, but to ecological causes. It is human mismanagement which has brought about a continuing deterioration in the natural conditions. Man has wantonly destroyed the original vegetation. Overgrazing, burning of lime and charcoal, as well as the ruthless exploitation of forest have caused the denudation of the country, thus exposing the soil to every form of erosion. Nothing much has been done in the way of afforestation, the beautiful newly planted pine forests in the Lebanon being an exception in this respect.

3. *Soils and Soil Formation*

(*a*) *General.* In the Mediterranean the soil scientist will hardly find well-developed horizons. Especially, soils *in situ* are of a skeletal nature, a shallow undifferentiated layer of soil overlying the parent rock. The intense insolation destroys most of the organic matter in the soil and causes mean soil temperatures of 40° C. and more in the summer months. In summer the movement of moisture is, naturally, upwards from below, so that we have a lower eluvial layer and an upper illuvial layer in the soil, whereby in extreme cases salt efflorescences or crusts may be produced. This capillary upward movement of water brings soluble salts to the surface, causing a relative richness in potassium and phosphoric acid. Wherever, as under forest, litter and humus accumulate, the latter is in the adsorptively saturated condition (mild humus), due in the first place to the presence of copious supplies of calcium. For this reason no translocation of iron and alumina due to the action of humic acids (podzolization) takes place. The soils seem never to be really acid, the lowest pH found by the author being 6·5. Even in the most humid parts of the country the pH is generally above 7. As pointed out elsewhere by the author (1947*a*), colloidal silica has a protective action on iron and alumina and may play an important role in soil formation under the conditions of the Mediterranean climate.

Where the mountains consist of hard limestone, weathering by solution naturally plays a major role. In the highlands are everywhere seen hollows, clefts, and fissures as a result of the solvent action of the carbonated water. In this way irregular structures arise, and the landscape

frequently appears to be dotted with blocks of rock or shows a strange accumulation of peaks and crags (*lapiez*) (Plate I). Hollows or pot-holes (*poljes*) are of frequent occurrence in the 'Karst' landscape.

Violent rainstorms scour the earth from the slopes down into the gorges, and the 'wadis', which in summer are dry, in winter frequently become filled with muddy, dark-coloured, roaring torrents, which can cause great devastation. Soil erosion is manifest everywhere and the valleys are therefore mostly filled by a deep and rich alluvial soil. On the other hand, especially in the Lebanon, well-built terraces have since antiquity protected the soil against erosion.

The accompanying soil maps can only give a schematic picture. They are based—apart from the lithological map of Dubertret (1943)—on climatic data as well as on observations made by the author. Due to the inaccessibility of the university laboratories on Mt. Scopus not all the soil samples taken have been analysed and no determinations of base exchange, organic matter, and nitrogen have been made. On the map of the eastern part of Syria no differentiation has been made between alluvial and other soils in the desert region. The following table shows the different soil types in their interdependence on the climatic factors:

TABLE 2

Climatic Regions and Soil Types of Syria and the Lebanon

Climate	*Rainfall*	*Rain-factor*	*Soil types*
Arid	100–200 mm.	0–20	Yellowish-brown desert soils. Hammada, Solontchak. Alluvial soils, dune sands, desert crusts.
Semi-arid	200–400 mm.	20–30	Mediterranean steppe soils (partly alluvial). Lava, desert crusts.
Semi-humid	400–*c.* 800 mm.	30–50	Terra rossa on limestone. Reddish and brown loams on igneous rock, mountain marls, red clayey sand soils, alluvial and conglomerate soils, sand dunes.
Humid	800 mm. and more	Greater than 50	Terra rossa on limestone, reddish and brown loams on igneous rock. Yellowish-brown clayey sands on sandstone.

We shall now turn to a description of the different soil types.

(*b*) *Desert soils.* The soils of the Syrian desert have been described by Muir (1951), and their geobotanical aspects have been dealt with by Zohary (1940).

As pointed out before, the northern part of the Syrian desert is a slightly undulating table-land, mainly built up by chalky marls. The climate of the desert causes ridges and hills to be buried under their own debris, the latter accumulating because of lack of water transport. In this way immense areas of flat or slightly undulating topography are formed. In the southern part, along the Jordan frontier, most of the area is a vast expanse of basalt mainly consisting of sharp-edged, wind-polished boulders.

The chalky marls give rise to undifferentiated, highly calcareous, yellowish-brown loam (Nos. 1, 2, 3, 6). With an excessive amount of

lime the colour assumes a whitish-grey (No. 4). Very often the surface consists of a 'desert mulch' of a few millimetres thickness. Various such soil profiles have been examined by Muir (1951), and the following analyses only confirm his data. It will be seen that the lime content of these soils is generally very high. Muir has established the presence of attapulgite with some kaolinoid and micaceous material in these loams.

Although none of the wadis has a perennial flow, the amount of water carried after the winter rains may be enormous. This water collects in shallow depressions, forming salt swamps or *sabkhas*. Such *sabkhas* are in consequence rich in salts and the soil assumes the character of a solonchak (No. 11). Similarly saline soils can be formed by improper irrigation practices, i.e. deficient drainage, on the banks of the Euphrates. Here barley is grown under irrigation and it will be seen that the soils have become quite saline (No. 8). A few miles farther west, cultivation has had to be abandoned, and the soil is covered by salt efflorescences (No. 9).

Many stretches of the desert are of the 'Hammada' type, i.e. the soil is covered by a carpet of angular, wind-polished fragments of flint and, in the southern desert, of basalt. This Hammada carpet owes its origin to the physical weathering of the rock, caused by temperature differences between day and night. The finest particles are afterwards eroded by wind action. Wind-blown sand, also highly calcareous, a product of calcareous sandstone, was observed by the author near Palmyra (No. 12).

TABLE 3. *Types and Composition of Desert Soils*

No.	*Soil type*	*Locality*
1	Yellowish-brown desert loam	Qtaife
2	" " "	Nasriye
3	" " "	21 miles past Qasre el Heir
4	Whitish marly desert loam	Soukhne
6	Yellowish-brown desert loam	14 miles south of Bir Mohaffir
8	Solonchak on desert loam	8 miles east of Sabkha (irrig. by Euphrates)
9	" " "	4 miles east of Sabkha (irrig. by Euphrates)
11	" " "	Near Bir Morarha (Aleppo–Palmyra track)
12	Calcareous dune sand	10 miles west of Palmyra
13	Yellowish-brown desert loam	Iraqi-Syrian Frontier
29	Yellowish marl	31 miles south of Homs

No.	*Gravel* %	*Lime* %	*Coarse sand* %	*Fine sand* %	*Silt* %	*Clay* %	H_2O %	*Sol. salts (mg./100 g.)* *Total*	Cl	HCO_3	CO_3	*pH*
1	31·0	36·6	5·5	26·1	10·8	18·3	3·0	..	..	..	..	7·4
2	5·6	32·7	1·5	27·4	17·9	18·2	4·0	..	..	..	..	7·6
3	12·5	40·7	3·7	32·2	4·9	16·5	2·3	..	..	..	..	7·5
4	1·6	56·0	0·6	11·8	8·3	20·1	3·4	..	..	..	..	7·4
6	10·6	13·2	1·3	63·8	8·8	11·1	2·2	..	..	..	..	7·3
8	0·8	17·9	0·8	18·8	45·8	9·0	7·3	570	10	199	..	7·3
9*	1·6	9·7	0·5	46·7	20·8	6·4	7·4	9,380	3,940	18	Tr.	8·7
11*	1·7	2·8	2·2	63·8	11·0	..	18·2	10,370	2,200	33	9	9·2
12	3·6	40·8	0·7	50·0	3·6	3·3	0·4	..	..	..	..	7·5
13	..	29·7	2·3	47·0	7·1	12·6	1·6	..	..	..	..	8·1
29	15·1	56·2	4·5	12·1	14·5	11·1	2·1	..	..	..	..	8·0

* SO_4 content of No. 9, 1·492, and of No. 11, 1·140 mg./100 g.

(*c*) *Semi-arid region.* Between the true desert and the Mediterranean area of Syria there intervenes a strip of country which may be best

described as steppe land. The same is true for the northern part of Syria, the land lying between the desert and the Kurdish foot-hills. In these areas rainfall is between 200 and 400 mm. and the rain factors are between 15 and 30. Under these conditions non-irrigated agriculture is still possible; it is the area where the battle between 'the Desert and the Sown', between the nomad population and the farmer, is taking place. The flora of grasses and herbs persists much longer after the winter rains than it does in the desert, and the whole area is an excellent grazing ground in spring. Here and there even isolated trees or small groves are found.

Chemical weathering of rocks plays a far greater role than it does in the desert and the soils contain a much higher percentage of true clay, i.e. of silicates of iron and alumina. The lime content, even on non-calcareous rocks, is still high and generally much higher than in the Mediterranean region. According to Muir (1951) the platiness observed in the desert soils disappears and gives place to a soft crumb structure. Terra rossa is not yet developing under the prevailing conditions of climate and this fact is rather striking when approaching, for example, the Aleppo region from the east. It is only in the more humid Aleppo region that the soils begin to assume a more reddish colour. Muir calls these soils, transitory to terra rossa, 'Red-brown Steppe Soils'. The absence of terra rossa under the prevailing conditions of climate is in agreement with observations made by the author in Israel, Jordan, Lybia, Cyprus, and Algeria (Reifenberg and Ewbank, 1933; Reifenberg, 1947*c*, 1947*b*). On the other hand, the soils have characteristics different from real steppe soils (chernozem or chestnut-coloured soils) and come nearest to the 'Brown and Grey Soils of the Semi-Desert' (Robinson, pp. 345 ff.). According to Muir (1951) the soils show a resemblance in their structural features to the sierozem of Turkestan. The author prefers for the time being the term 'Mediterranean Steppe Soil' which expresses the important influence of the rainless summer on soil development (destruction of organic matter by insolation, upward movement of water).

We find this type of soil not only on limestone, but also on basalt (Nos. 39, 43, 44, 45), conglomerates (Nos. 20, 21), sandstone (46), &c. Alluvial soils in this region show similar characteristics; they are, however, usually much heavier and deeper and they thus form one of the most fertile soil types of the region. Especially the basalt soils show deep cracks in summer (Nos. 44, 45). Rich alluvial soils partly derived from limestone and partly from basalt (Nos. 36, 37, 38, 41) cover most of the Jezireh, where out of an area of 2,500,000 acres only about 780,000 acres are cultivated today. At the same time there are very great irrigation possibilities in the Jezireh. It will be seen that most of the basalts weather to a brownish colour. Not so, for example, the rich basaltic soils of the Hauran. Here the colour is more reddish, probably due to a difference in mineralogical composition (No. 19). In the same region, however, are late flows which have not yet suffered any chemical weathering at all. Due to different circumstances of solidification the lava streams show strange forms of cracked masses, sometimes several

metres high. This lava landscape is impossible to penetrate and the 'Ledja' (country of refuge) has for centuries been a hiding-place for all enemies of the law. The following tables give the types and composition of some of the Mediterranean Steppe Soils:

TABLE 4

Types and Composition of Mediterranean Steppe Soils

No.	*Soil type*	*Locality*
19	Reddish basaltic clay loam	Sheikh Meskene
20	Yellowish sandy loam on conglomerates	20 km. south of Damascus
21	" " "	Cross-road Damascus–Ain Fije
28	Black alluvial clay	16 km. south of Taftenaz
36	Alluvial clay loam	Ain Arous
37	Reddish alluvial clay loam	10 km. east of Ain Arous
38	Reddish alluvial (limestone and basalt) clay loam	Past Tel Bandar
39	Brownish basaltic clay	Tel Hajjeb
40	River silt	Tel Shioukh (Euphrates)
41	Reddish alluvial soil	West of Tel Chair
42	Yellowish-brown loam	23 miles west of Ras el Ain
43	Brownish basaltic clay loam	9 miles east of Kamichliye
44	Blackish basaltic clay loam	Tel Kotchek
45	Brownish basaltic clay loam	Demir Kapu
46	Sandy soil	14 miles east of Demir Kapu

No.	*Gravel* %	*Lime* %	*Coarse sand* %	*Fine sand* %	*Silt* %	*Clay* %	H_2O %	*Sol. salts (mg./100 g.)* *Total*	Cl	HCO_3	CO_3	*pH*
19	5·6	4·2	0·6	20·2	13·3	53·1	7·9	..	..	..	..	7·4
20	4·2	36·3	2·5	20·3	8·3	30·5	3·1	..	..	..	..	7·4
21	7·9	66·4	6·6	8·1	8·0	10·6	0·4	..	..	..	..	8·0
28	8·3	8·9	1·4	8·2	12·4	63·2	6·1	..	..	..	..	7·5
36	10·8	28·5	2·9	14·6	13·5	36·4	5·9	..	33	45	..	7·3
37	..	22·3	0·7	19·6	17·7	33·4	5·3	240	5	70	..	8·1
38	17·0	29·7	4·1	13·1	13·6	34·5	4·1	280	7	93	..	7·8
39	2·0	21·3	0·5	5·1	12·9	54·9	5·8	..	10	56	..	8·1
40	0·3	13·9	0·7	73·3	2·9	5·8	2·0	..	5	45	..	7·7
41	7·0	19·9	1·6	8·4	13·5	52·0	3·0	100	..	..	..	7·8
42	11·1	30·7	8·2	8·2	14·6	34·4	3·9	..	..	..	..	7·3
43	2·7	21·9	0·5	10·2	20·0	49·3	5·1	..	15	82	..	7·5
44	..	21·3	0·5	15·1	18·0	41·8	4·3	..	..	..	..	7·1
45	..	21·3	0·9	12·0	13·6	47·0	4·5	..	..	..	..	7·5
46	0·2	9·0	4·1	77·5	3·3	4·0	1·2	..	..	..	..	7·1

(*d*) *The semi-humid region.* To the west of the steppe land and in some isolated districts to the north extends a region which, because of its proximity to the sea or because of higher altitude, is much more favoured by rainfall (400 mm. and more, rain factors 30–50). Here we meet with soils typical for Mediterranean countries, first and foremost terra rossa. The hard-fissured limestones which are of great permeability and are easily attacked by rain water yield, as everywhere in the Mediterranean, typical terra rossa. The Jurassic limestones in particular show very often a typical Karst landscape with 'karren' (*lapiez*) formation, dolines, &c. (Dubertret, 1943). The pattern of terra rossa formation was dealt with previously by the author (1947*a*) and the profiles observed were so similar to terra rossa formation in Palestine and elsewhere that no profiles were taken. The following definition given by the author (1947*a*) holds good also for Syria and the Lebanon: 'Terra

rossa develops on limestone under the conditions of the Mediterranean climate. In comparison with its parent material, the limestone, it has been greatly enriched in sesquioxides and silica. In comparison with the soils of humid climates, it contains large quantities of salts of the alkalies and alkaline earths. The high iron content together with the low humus content are responsible for the red colour, which is often brilliant. They are mostly soils with an alkaline reaction and loamy structure; they may contain calcareous and ferruginous concretions.' The author explains the origin of terra rossa and the increase of sesquioxides in the soil partly by the protective action of colloidal silicic acid (1947*a*). Muir (1951) makes the interesting remark that by calculating the gains and losses from the parent material the figures point rather to a loss and not to an increase of iron. This loss, according to Muir, may be caused by the aforementioned mechanism, i.e. peptization of iron by silica. It is quite possible that there may also be a loss of iron during the rainy season and it is agreed that in most cases the relation of silica to iron is much narrower in the limestone than it is in the resulting soil. The author has, however, stressed the fact that both silica and sesquioxides become increased in the soil. The main point, however, is that, in comparison with arid or cold-humid soils, the iron content is much higher in the terra rossa. This refers not to a comparison with the Si/Fe quotient in the parent rock but to the absolute figures.

Muir (1951) has further shown that the constituent minerals in Syrian terra rossa are essentially a kaolinoid of 'mellorsitic' composition with some quartz, haematite, and mica.

When not protected by terracing the terra rossa soils are liable to erosion and form very fertile colluvial soils in the plains and valleys. Although no profiles were taken, a few samples may illustrate the nature of Syrian terra rossa soils. Sample No. 10 is the weathering product of a coarse, poorly compacted, porous, and fissured limestone of Miocene age which covers large areas in northern Syria (Dubertret, 1943) and is very liable to 'crust' formations. This soil borders the steppe region and is exceptionally rich in lime. No. 5 is a colluvial soil and has suffered much transportation (it overlies sandstone). No. 30 has suffered even greater decalcification.

Red sandy soils occur on coastal formations (calcareous sandstone) and are found near Beyrouth, Tripoli, &c. The processes leading to their formation may be similar to the mechanism of heterogenization of minerals in moving dunes as described by Rim (1951).

Mountain marls also cover wide areas in Syria and the Lebanon.

In contrast to the hard limestones the chalky marls never weather to terra rossa, but preserve their whitish or greyish colour. This may partly be due to the predominance of chalk, and partly to the fact that rocks of this kind do not allow for real soil formation, but merely weather to a rock meal or marl with lime contents of over 50 per cent. True hydrolytic processes characteristic of the evolution of soils do not take place here. The chief action consists in the solution and erosion of the products of disintegration. The soft and dense rock is generally impermeable to water and no downward movement of water takes place.

According to Zohary (1942) these marly soils are vegetationally well distinguished from terra rossa, and the regeneration of the arboreal Mediterranean association seems to be impeded on these soils. Such mountain marls cover much of the lowlands, and notwithstanding their high lime content and bad water-holding capacity they are intensely cultivated by terrace culture.

Basalts usually weather to *Reddish or Brown Loams*, the colour of the latter often assuming a chocolate-brown shade. These differences in colour may be partly explained by the differences in colour between ferric-oxide and ferrous-oxide silicic-acid sols, ferrous compounds being predominant in basalt rock (Reifenberg, 1947*a*). Obviously the mineralogical composition of the basalt will also greatly influence the resulting soil, as was shown for Syrian conditions by Muir (1951), who found (near Homs) in one variety a kaolinoid clay mineral together with a vermiculite-like material and goethite. In another soil derived from glassy basalt he found as dominant clay mineral a montmorillonoid with goethite and amorphous oxides. Quite generally the soils, whether derived from limestones or basalts, are very similar in their chemical composition and in their qualities. This shows again the predominant influence of climate which, in spite of the greatest difference between the parent rocks, can produce soils having similar chemical composition. Usually, of course, basalt soils are much poorer in calcium carbonate (Nos. 34 and 35) and, as will be shown below, limestones tend to increase the 'siallitic' character of the red soils of the Mediterranean, i.e. in the absence of calcium carbonate more silica and possibly also iron is removed by leaching. It should, however, be emphasized that some basalt soils contain very appreciable amounts of lime (No. 45).

An interesting example of basaltic sea sand containing grains of volcanic glass was found by the author near Banias (south of Lattaqie; No. 31). Here basaltic rock reaches the sea and the black sand is a result of the eroding action of the surf.

Dune sands do not have such an extent as, for example, in Israel. They are found near Tyre, Beyrouth, and Tripoli and have been transported by longitudinal sea currents coming from the south. Whenever these currents meet with an obstacle, as e.g. near Tyre the dam built by Alexander and near Beyrouth and Tripoli the promontories, dune sand accumulates in front of these obstacles (No. 22). Further north these dune sands become mixed with alluvial material brought down from the mountains (No. 23).

(*e*) *The humid region.* It was pointed out before that at high altitudes rainfall may be well above a thousand millimetres and the average monthly temperature 12° C. and below. Rain factors are therefore well above 50 and may even reach 100 and more. Such high rain factors are found in Mt. Lebanon, the Antilebanon, the Hermon region, the Ansariye Mountains, and in the foot-hills of the Taurus. It has been maintained (Muir, 1951) that under such conditions terra rossa gives way to brown forest soils and even to podzolic soils towards the summits. The author has not found any signs of real podzolization, and even under forest the character of the soils does not seem to have changed considerably. It is

TABLE 5

Types and Composition of Soils in the Semi-humid Zone of Syria and the Lebanon

No.	*Soil type*	*Locality*
5	Alluvial terra rossa	Qatane
10	Terra rossa	Nirab
30	Terra rossa	16 km. south of Baalbek
34	Reddish alluvial basaltic clay loam	3 km. north of Homs
35	Red basaltic clay loam	2 km. north of Rastane
47	Brownish basaltic clay loam	6 km. west of Ain Divar
31	Black basaltic sea sand	5 km. north of Baniyas
22	Calcareous dune sand	25 km. north of Tripoli
23	Brownish loam	43 km. north of Tripoli

No.	*Gravel* %	*Lime* %	*Coarse sand* %	*Fine sand* %	*Silt* %	*Clay* %	H_2O %	*pH*
5	..	13·8	2·1	12·0	10·8	52·3	9·6	7·3
10	12·2	36·6	5·4	4·3	7·7	39·6	6·2	7·3
30	14·8	0·7	1·4	13·7	46·9	28·6	7·9	7·4
34	12·5	1·6	1·2	13·5	32·9	41·0	8·4	8·1
35	9·6	1·5	1·5	31·0	10·8	50·3	7·9	7·7
47	19·2	13·1	1·8	9·1	15·3	55·1	6·2	7·6
31	42·2	1·1	72·0	23·6	0·2	5·1	2·6	8·9
22	1·0	40·4	0·9	54·8	1·2	3·3	0·3	8·1
23	68·4	3·1	2·3	44·1	16·1	30·2	4·8	8·2

obvious that under forest the soil will be covered by litter and the organic-matter content may be higher than usual. It may be that more detailed examination of the regions concerned may prove the existence of brown forest soils; for the time being, however, the author is not inclined to use this designation for the mostly reddish-brown loams at high altitudes of Syria and the Lebanon. Apparently the summer-dry period with its influence on the organic matter and the upward movement of the soil solution influence soil formation much more than the abundance of winter rains.

Very much will depend on the nature of the parent material. On hard limestones we will again meet with terra rossa, and wherever lime is present in the parent rock, even in the case of serpentines or sandstones, there will be no leaching of carbonates and the reaction will remain slightly alkaline. Only in exceptional cases will the reaction be slightly acid, and even soils overlying lime-free rocks (basalts and gabbros) are generally moderately alkaline. With the exception of a gabbro which has weathered to a greyish soil, the predominant colours of soils at high altitudes are reddish or brownish according to the nature of the parent rock.

In the weathering process the presence or absence of lime seems to be decisive. In the case of limestone, the action of the large amount of calcium hydroxide—formed by the dissociation of calcium carbonate—and of other electrolytes coagulates most of the silica and the sesquioxides. These compounds are coagulated and retained in the soil, which therefore contains more silica, iron, and alumina than the parent rock.

On lime-free igneous rocks, on the other hand, there seems to be some loss of silica and possibly also of iron. These observations are in general agreement with observations made by the author in Cyprus (Reifenberg and Ewbank, 1933).

In order to study the processes involved the author has made a detailed examination of profiles developed on basalt, gabbro, serpentine, and sandstone.[1]

A. *Soil profile on basalt.* The profile No. 18 has been taken 5 km. north-west of Banias on the slopes of Mt. Hermon. Rainfall is approximately 900 mm. and the mean temperature in winter about 14° C. The rain factor is therefore about 64. The landscape is very rugged and the sloping land resembles Karst country. The thin soil is covered by angular boulders. The vegetation consists of low shrubs. The profile may be described as follows:

TABLE 6

I. 0–20 cm. Brownish loam of cloddy structure.
II. 20–30 cm. Weathered basalt zone. Strongly decomposed with pockets of soil. The olivine has assumed a yellowish colour.
III. Black basalt with felspar, augite, and olivine.

*Analysis of Basalt Profile**

	III Basalt	*II Decomposition zone*	*I Brownish loam*
SiO_2 %	45·05	37·93	46·80
Al_2O_3 %	16·00	36·99	27·09
Fe_2O_3 %	7·55	8·33	8·76
FeO %	3·73	0·66	2·37
CaO %	15·47	5·20	6·70
MgO %	8·00	3·76	3·55
K_2O %	1·44	3·26	1·86
Na_2O %	1·06	0·90	1·75
P_2O_5 %	1·71	2·94	1·31
Cl %	..	0·01	0·01
Si/Al	4·8	1·7	2·9
Si/Fe	10·3	10·8	10·9
Si/R	3·2	1·5	2·2
In original samples			
CO_2 %	..	..	..
H_2O- %	0·64	3·81	3·80
H_2O+ %	0·86	6·19	8·10
N %	..	..	0·18
pH	..	..	7·5

* All results in this paper are given on a basis excluding loss on ignition, but in order that the reader may calculate the percentage composition of the layers, as taken, the percentage of each volatile constituent in those layers is also given. The loss of water above 105° (H_2O-) also includes very small amounts of organic matter.

[1] The author wishes to thank his former assistants Dr. T. Menahem-Starkmann, Mrs. R. Rasovsky, and Mr. Banias, M.A., for their help in the analytical work.

Mechanical Analysis of Brownish Basalt Loam

	%
Coarse sand	3·96
Fine sand	36·84
Silt	24·78
Clay	27·40
Lime	..
Water	3·80

It will be seen that some of the ferrous iron has been oxidized; strangely enough, there is much less of it in the decomposed zone than in the soil. The Si/Fe ratio has remained constant. Since obviously silicic acid has been removed from the decomposition zone, iron must have been lost too. This may explain the low ferrous-iron content in zone II. Alumina has greatly increased in the decomposition zone, whereas the alkaline earths have suffered great losses. The high content of hydration water shows the progress of weathering.

Most of the silicic acid and ferrous iron lost in the decomposition zone has apparently moved into the soil by ascension. In any case, in comparison with the parent rock, the resulting soil does not show a loss either of silicic acid or of sesquioxides.

B. Profile on gabbro. This profile (No. 27) was taken in the foot-hills of the Taurus Mountains on the road from Lattaqie to the Turkish border, at a point 2 km. south of the border. Rainfall in this region is above 1,000 mm. and the rain factor will be above 80. The vegetation consists of a park-like forest of Aleppo pine.

A description of the profile is given in Table 7.

A considerable part of the alkaline earths has been lost in the decomposition zone. Some silicic acid may have been removed from the zone. Iron, on the other hand, is greatly increased here. In the soil itself a still greater proportion of the alkaline earths has been leached and the loss in comparison to the rock is over 70 per cent. This loss of alkaline earths and the loss of iron is not fully sufficient to explain the very great increase of silica in the soil. It seems plausible that a small proportion of the silica increase in the soil is to be explained by the accumulation of quartz. In this connexion it may be mentioned that in the clay fraction of the soil Si/Al is 3·5; Si/Fe 12·6 and Si/R 2·7. The iron content in the soil is much smaller than in zone II, and in this case it may be assumed that part of the iron has been leached and has accumulated in the decomposition zone.

This leaching of iron may account for the grey colour of the soil and the yellowish tinge of the decomposition zone. Although the reaction is still moderately alkaline, the heavy leaching of Ca and Mg and the practical absence of coagulating carbonates may be responsible for this unusual downward movement of iron. A similar greyish soil-colour was observed in the case of an alluvial soil, derived from igneous rock, which had the slightly acid reaction of pH 6·7. (This sample was taken on the same road 8 km. farther south of the serpentine profile.)

TABLE 7

I. 0–20 cm. Greyish clay loam.
II. 20–25 cm. Yellowish decomposition zone of coarse-grained gabbro.
III. 25 cm. Grey, partly decomposed, coarse-grained gabbro with light coloured plagioclase and anorthite and dark-coloured pyroxenes.

Analysis of Gabbro Profile

	III *Gabbro*	*II* *Decomposition zone*	*I* *Grey clay loam*
SiO_2 %	56·55	56·99	73·96
Al_2O_3 %	6·65	7·71	8·17
Fe_2O_3 %	10·17	14·48	8·35
FeO %	0·29	0·47	0·55
CaO %	10·18	8·45	3·12
MgO %	15·89	10·17	4·05
K_2O %	Tr.	0·20	0·07
Na_2O %	Tr.	1·42	0·60
P_2O_5 %	0·31	0·37	0·47
Si/Al	14·5	12·9	15·4
Si/Fe	14·3	10·1	21·9
Si/R	7·2	5·6	9·1
In original samples			
CO_2 %	0·45	..	0·30
H_2O- %	2·81	4·58	6·14
H_2O+ %	3·91	7·93	7·24
pH	..	..	7·2

Mechanical Analysis of Grey Clay Loam

	%
Coarse sand	1·48
Fine sand	29·13
Silt	18·93
Clay	43·37
Lime	0·68
Water	6·14

It would be premature to suggest that because of the leaching of iron and the grey colour of the soil it should be classified as belonging to the class of (greyish) brown forest soils. There is no humus horizon and the reaction is still moderately alkaline. Only a more detailed study of soil profiles in this region will solve this question.

C. Profile on serpentine. This profile (No. 26) has been taken on the same road as the gabbro profile about 24 km. south of the Turkish border. Here, too, rainfall exceeds 1,000 mm. (rain factor above 80) and scattered Aleppo pines cover the ground. The profile may be described as follows:

TABLE 8

I. 0–30 cm. Reddish-brown loam with sparse organic material.
II. 30–40 cm. Decomposed zone of serpentine with crumbling brownish fragments.
III. Dark green serpentine with slicken sides.

Analysis of Serpentine Profile

	III *Serpentine*	*II* *Decomposition zone*	*I* *Reddish-brown clayey loam*
SiO_2 %	46·00	75·84	62·74
Al_2O_3 %	1·95	0·43	5·61
Fe_2O_3 %	3·46	8·11	8·76
FeO %	1·95	0·72	0·82
CaO %	6·56	10·74	8·21
MgO %	38·52	2·80	10·32
K_2O %	0·02	0·75	1·12
P_2O_5 %	0·64	0·54	0·47
Na_2O %	0·40	1·46	1·44
Si/Al	38·4	304·8	19·0
Si/Fe	20·8	22·7	17·3
Si/R	13·5	21·1	9·1
In original samples			
CO_2 %	0·56	4·31	1·01
H_2O- %	2·30	1·86	5·19
H_2O+ %	10·30	1·66	4·66
pH	..	..	8·2

Mechanical Analysis of Reddish-brown Clayey Loam

	%
Coarse sand	5·85
Fine sand	32·37
Silt	18·30
Clay	36·30
Lime	2·30
Water	5·19

The most spectacular loss in the decomposition zone is that of magnesia, of which over 90 per cent. has been removed. This loss may explain the relative increase of calcium in this zone, but not all of the silica increase. There has been a very great loss of alumina in zone II. Iron has relatively increased due to the loss of other constituents; the Si/Fe ratio has remained practically constant. The greater part of the ferrous iron has suffered oxidation. The alkali salts have increased both in the decomposition zone and in the soil. The increase of alumina and magnesia in the soil may be explained by the movement of both these constituents by ascension from the decomposition zone. There has been some loss of silicic acid from the soil, but in comparison with the parent rock there has been an increase of both sesquioxides and silica.

Notwithstanding the high rainfall the serpentine has weathered to a reddish-brown Mediterranean soil, very similar to serpentine soils

which were formed under similar climatic conditions in Cyprus (Reifenberg and Ewbank, 1933).

D. Profile on sandstone. The profile (No. 33) was taken past Ain Sofar railway station at 1,280 m. altitude in the Lebanon. Rainfall will be above 1,000 mm., the mean winter temperature about 10° C., and the rain factor therefore above 100. Vegetation is very sparse. The following samples were taken:

TABLE 9

I. 0–40 cm. Yellowish-brown clayey sand.
II. 40 cm. Yellowish sandstone with many iron veins and iron concretions.
IIa. Blackish iron veins with metallic lustre in sandstone.

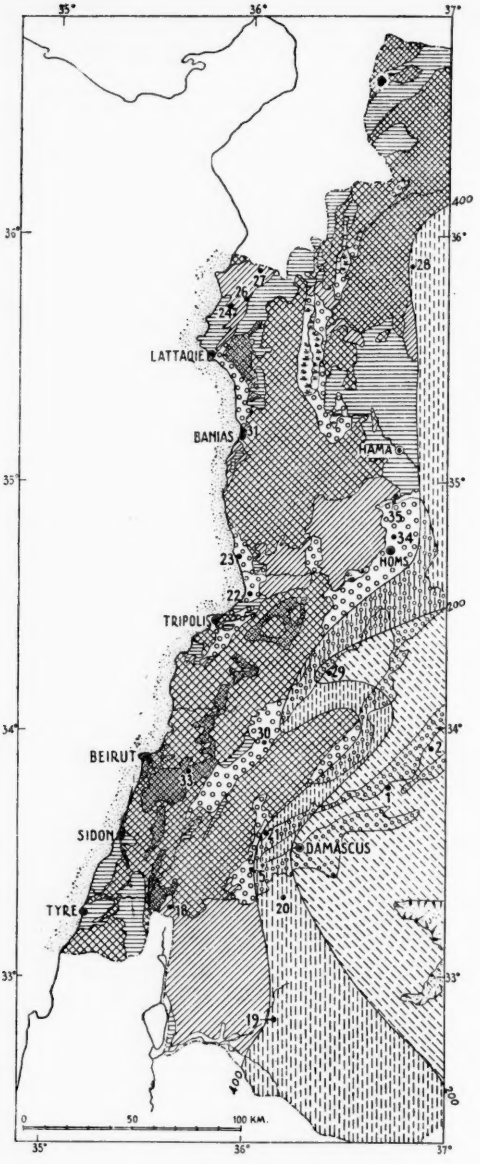
Analysis of Sandstone Profile

	II Sandstone	*IIa* Iron-veins in sandstone	*I* Clayey sand
SiO_2 %	92·28	75·90	66·27
Al_2O_3 %	1·71	0·49	1·43
Fe_2O_3 %	4·27	20·41	24·19
FeO %	0·46	Tr.	0·75
CaO %	0·25	0·68	5·79
MgO %	0·01	Tr.	Tr.
P_2O_5 %	0·23	0·13	0·75
K_2O %	0·01	..	0·46
Na_2O %	0·07	..	0·56
Si/Al	91·6	274·5	78·9
Si/Fe	51·4	10·4	7·1
Si/R	32·9	10·0	6·5
In original samples			
CO_2 %	0·22	0·38	2·84
H_2O- %	0·50	0·89	2·59
H_2O+ %	1·17	3·22	6·33
pH	..	..	8·0

Mechanical Analysis of Clayey Sand

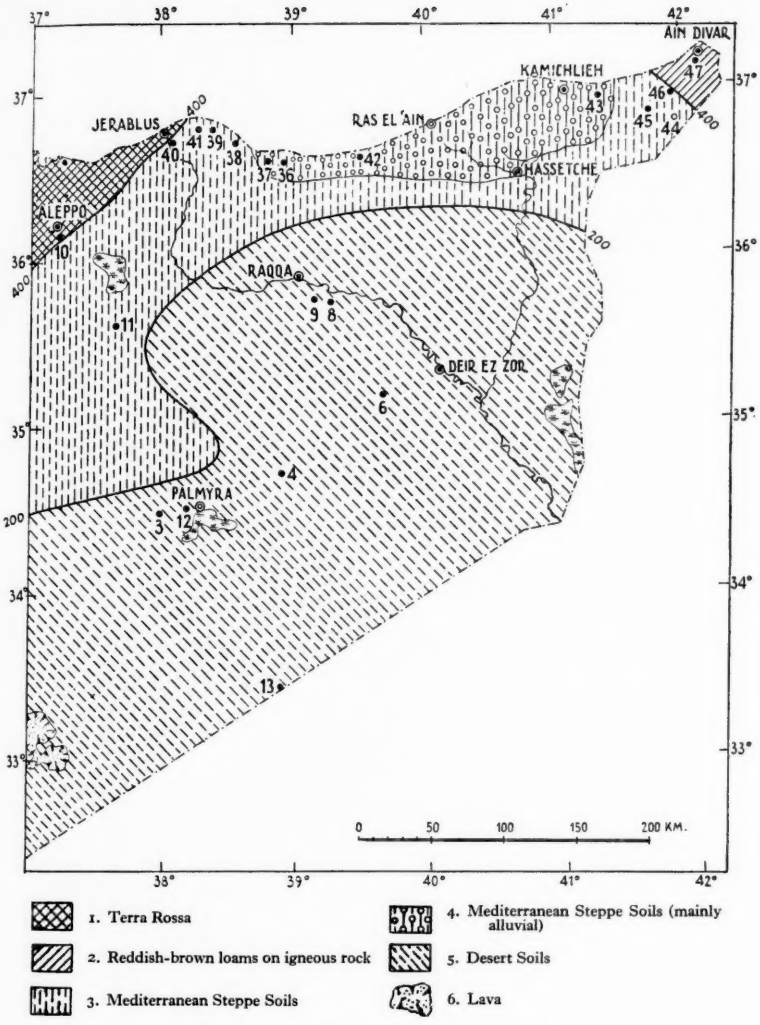
	%
Coarse sand	3·94
Fine sand	57·28
Silt	6·58
Clay	23·57
Lime	6·45
Water	2·59

The decrease of silicic acid in the soil is only a relative one and is due to the great increase in iron. Since there is no decomposition zone this increase in iron can only be explained by ascending iron solutions in the sandstone. These ascending iron solutions, protected by silicic acid, explain the presence of iron veins, which practically consist of iron and silica only. Calcium carbonate and alkali salts are increased in the soil notwithstanding the extremely high rainfall. The increase in sesquioxides



1. Terra Rossa
2. Reddish-brown loams on igneous rock
3. Mediterranean Steppe Soil
4. Mediterranean Steppe Soil (alluvial)
5. Desert Soils
6. Desert Soils (alluvial)
7. Yellowish-brown clayey-sands
8. Mountain Marls
9. Alluvial Soils (including conglomerate soils and sand dunes in the coastal plain)
10. Lava

Schematic Soil Map of Western Syria and the Lebanon



Schematic Soil Map of Eastern Syria

is also reflected in the Si/R quotient in the clay fraction of the soil (Si/R = 1·8). Such moderately alkaline yellowish-brown soils are typical for the sandstone region of Mt. Lebanon.

Summary

A schematic soil map of Syria and the Lebanon is given. The country is divided according to climatic data into arid (rain factors 0–15), semi-arid (rain factors 15–30), semi-humid (rain factors 30–50), and humid (rain factors above 50) zones. The soils of each region are described. Soil profiles taken in the humid zone do not suggest podzolization processes. Notwithstanding the high rainfall in winter, the dry summer period has a decisive influence. The dryness in summer does not allow the formation of acid humus, and the soils are generally moderately alkaline. There is generally no complete leaching of lime and alkali salts due to the capillary upward movement of water in summer. Soil formation is greatly influenced by the nature of the parent rock. In the semi-humid and humid zones terra rossa on limestones and reddish-brown loams on igneous rocks predominate as everywhere in the Mediterranean region.

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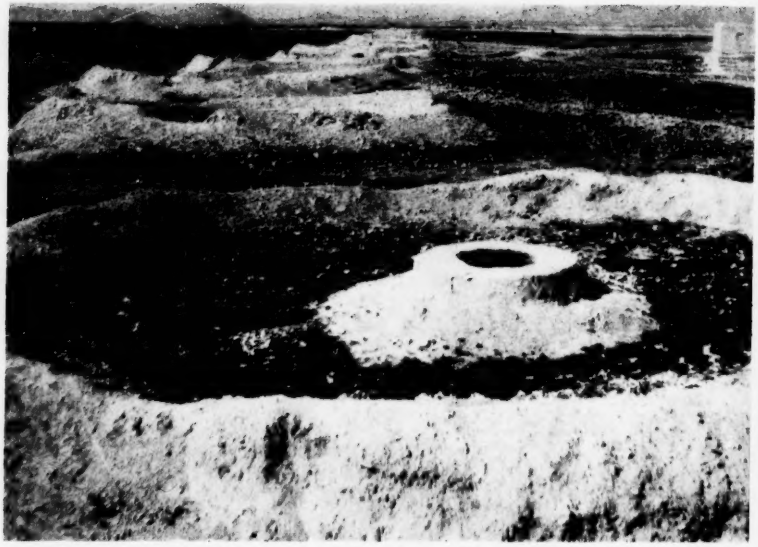
(*Received 2 August 1951*)

1. Badly eroded 'Karst' landscape in Mount Lebanon (p. 77).

2. Silted up irrigation channel near Raqqa. This desert region was once intensely irrigated (p. 71).

A. REIFENBERG—PLATE I



3. *Foggaras* in the desert, east of Damascus. Deep shafts sunk in the desert-soil are interconnected by a subterranean channel to collect the drops of water yielded by each shaft. The water of this channel is then used for irrigation. These Roman shafts were cleaned and are again in use today (p. 71).

4. Terra rossa landscape north of Beyrouth. Well-kept natural terraces. The eroded soil forms most fertile agricultural land in the plains (p. 78).

A. REIFENBERG—PLATE II

STUDIES IN PEDOGENESIS IN NEW SOUTH WALES

I. THE INFLUENCE OF RICE CULTIVATION ON THE GREY AND BROWN 'GILGAI' SOILS OF THE MURRUMBIDGEE IRRIGATION AREAS

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THE Murrumbidgee Irrigation Areas of the northern Riverina of New South Wales, like most irrigation schemes, lie in a region of relatively low rainfall. They were originally developed for horticulture on the lighter soils and irrigated pastures for dairying on the heavier soils. This latter system of husbandry proved at the time to be uneconomic and, as an alternative, rice cultivation was introduced about 26 years ago. Under the system used, water to a depth of 8 in. is maintained over the entire surface of the soil on which the rice is sown. The quantity of water required to maintain this head against losses by seepage, transpiration, and evaporation is relatively large, averaging 7 acre-feet over the whole of the areas, some blocks using twice this quantity.

The soil environment has consequently been changed from one of relative aridity to one of periodic humidity. This study was undertaken in an attempt to discover the extent to which this change in environment has been reflected in the internal characters of the soils.

Description of the Areas

The rice-growing areas are grouped to the west and north-west of the town of Leeton, within a radius of about 20 miles. Survey of the area by England (1942) showed the non-horticultural soils to be of three types: brown self-mulching soils, fairly heavy-textured red-brown earths, and a third group described as grey and brown 'crabholey' soils.[1] The latter group is the most important for rice-growing, and carries 60 per cent. of the rice crop. All the soils sampled in this study were from this group.

Although the soil types appear much the same over the entire area, deep boring has shown (England, 1942) that the superficial deposits are underlain by two totally different types of strata. To the south of the area the soil is underlain by permeable sand beds, and to the north by impermeable clays. The records of water consumption on rice farms kept by the Irrigation Commission show that the quantity of water used is largely governed by the nature of the underlying strata. Average

[1] 'Crabhole' or 'crabholey' is a term used to describe the surface undulations that are a common feature of clay soils in semi-arid and sub-humid parts of Australia. In this part of New South Wales, where the surface undulations become too marked to allow the land to be graded down for irrigation, it is described as 'gilgai' rather than 'crabhole'. In other parts these two terms, and such others as 'melonhole', are used as synonyms. An account of this feature will be given elsewhere. In the meanwhile all soils showing this feature are described collectively by the term 'gilgai'.

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figures for mean annual water consumption during rice irrigation on the areas from which samples were taken are for the areas underlain by permeable sands 8·5 acre-feet, and for the areas underlain by impermeable clays 6·8 acre-feet. The difference between the means is significant at the 5 per cent. point. The difference in water consumption between the areas is greater than is shown by these figures, since where the consumption was greater than 10 acre-feet it was treated as 10 in the analysis.

The area can be considered as an experimental layout on which various treatments in the form of varying numbers of rice crops have been applied to the soil over a period of 20 years. Half of the total sampling sites were selected from each of the two blocks defined by the nature of the underlying strata. Since 1926 detailed records of the areas sown to rice have been kept by the Water Conservation and Irrigation Commission. Each year maps have been drawn showing the areas of rice cultivation. From these maps it is possible to trace the rice-growing history of any part of a farm since 1926, and the areas can be selected and grouped according to the number of rice crops that have been grown. When sampling was undertaken in August 1946 it was thus possible to obtain 8 replications which had carried 1, 2, 3, 4, 5 and 6 rice crops respectively, but only 5 replications could be obtained for areas which had carried 7 rice crops. Some irrigated soils which had never carried rice were also sampled, whilst 6 uncultivated and unirrigated sites were obtained on each block.

Sampling procedure. A spade and a 4-in. post-hole auger were used to obtain the samples. The surface soil was first removed to a depth of 4 in. It was spread on a piece of sacking, and extraneous matter consisting mostly of undecomposed vegetation was removed. After thorough mixing a sample of 3-4 lb. was taken. The auger was used to obtain samples from 4–15 in., 15–30 in., and 40–48 in. In each case the soil was mixed and spread as above before taking the sample.

In the laboratory the samples were finely ground in a Christy Norris Laboratory Mill, moist samples being previously air-dried. One hundred and thirty-nine profiles were sampled in this manner, and the following laboratory data were obtained: pH (Doughty, 1941; McGeorge, 1945); sulphate after extraction with 5 N-HCl for 30 minutes; carbonate (Collins calcimeter); nitrogen; organic carbon (Schollenberger, 1945); chloride (Best, 1929). Exchangeable bases and exchange capacity were determined after removal of soluble salts by using 50 per cent. ethyl alcohol.

In the lower horizons where concretionary calcium carbonate was present, the exchangeable calcium figure was obtained by subtracting the sum of magnesium, potassium, and sodium from the exchange capacity, all in milli-equivalents.

The Characters of the Soils

In this study no mechanical analyses of the soils were undertaken, but according to figures published by Prescott (1932), soils of this type contain 50–60 per cent. clay and less than 10 per cent. coarse sand.

Chemical analyses of virgin soils are given below in Table 1.

TABLE 1

Chemical Analyses of Virgin Crabhole Soils

(Figures are the means of six sites, except for chlorides of 0–4 in., 4–15 in., and 15–30 in. depths, which are the means of three sites)

Depth	*0–4 in.*		*4–15 in.*		*15–30 in.*		*40–48 in.*	
Subsoil	*Permeable*	*Impermeable*	*Permeable*	*Impermeable*	*Permeable*	*Impermeable*	*Permeable*	*Impermeable*
pH	5·17	5·28	6·73	7·08	7·68	7·81	7·71	7·80
Chlorides mg./100 g.	3·0	4·7	6·6	22·7	22·7	57·3	61·3	83·7
Sulphates mg./100 g.	0·0	0·0	0·0	0·0	0·0	0·0	303·6	76·3
Nitrogen %	0·102	0·105	..	..	..	..	..	..
Exchange capacity and cations—expressed as m.e. per 100 g. soil (mean of three sites)								
Exchange capacity	26·0	19·3	33·3	28·3	35·7	29·1	32·7	27·7
Total bases	18·89	14·18	30·86	29·09	49·59	47·78	42·09	46·61
Calcium	14·77	11·64	22·68	21·73	25·36	30·40	21·27	18·41
Magnesium	2·72	1·07	4·94	2·95	6·13	3·66	6·43	3·58
Potassium	0·97	0·89	0·81	0·87	0·55	0·71	0·66	0·71
Sodium	0·76	0·53	1·89	2·22	3·67	4·30	5·30	5·00

As can be seen from the figures, in the virgin state the soils are acid in the surface, approach neutrality at about 4 in., and become alkaline at lower depths. Those overlying permeable subsoil appear to be slightly more acidic than those over the impermeable subsoil. The chlorides show a progressive increase into the lower horizons, and those soils overlying permeable subsoil show lower chloride figures at all depths than do the soils over the impermeable subsoil. No sulphate, or only a trace, is found in any soil above 30 in., but it appears as a distinct layer of gypsum at 40 to 48 in. By contrast with the figures for chlorides, sulphates are distinctly higher in those profiles overlying permeable subsoils. The nitrogen content is the same over both types of subsoil.

In accordance with the pH figures, the exchange complex shows a moderate degree of unsaturation for the surface 4 in., and below this level it is fully saturated. For both groups of soils, calcium is the dominant cation, although using the convention adopted here to obtain exchangeable calcium for those horizons containing calcium carbonate, the proportion that calcium constitutes of the exchangeable cations falls somewhat at lower depths. Exchangeable potassium is relatively high at 0·9 to 1·0 m.e. in the surface soil, but also falls steadily with increasing depth, whilst magnesium and sodium both increase in the lower horizons. Exchangeable magnesium is lower for all horizons for those soils overlying the impermeable subsoils, but this difference is of doubtful significance.

Trends in Soil Characters due to Rice Irrigation

It is to be expected that any form of irrigation will have some effect on the characteristics of the soil. The particular effects of rice irrigation will be due to the condition of total flooding for part of the year. Unless the soil type is very impermeable, the maintenance of a constant depth of about 8 in. of water above the soil surface will result in greater infiltration, and consequently in much greater leaching effects, during a rice-growing season than would occur when the soil moisture is brought to field capacity once or twice during the growing season as would be the case when wheat or oats is the crop. The extent to which this effect operates can be gauged from the figures for water consumption during the rice-growing season, that vary from 6 to 16 acre-feet with a mean over the whole rice area of 7 acre-feet. A small percentage of this water would be drained off the surface at the end of the growing-season, and a much larger proportion would be evaporated. Since the mean annual rainfall at Leeton is 16·15 in., rice irrigation results in the application of from 6 to 12 times the amount of water that would be applied to the soil under natural rainfall.

A second effect of the rice irrigation may be contrasted with conditions existing under natural rainfall. The mean annual rainfall is spread as falls of varying intensity throughout the year, with a slight winter maximum. Between successive falls of rain the surface soil dries to a greater or lesser extent, and movement of water downwards through the soil stops and may be reversed. During rice irrigation, on the other hand, there are no alternations of wet and dry conditions of the surface soil, and the movement of water through the soil is downwards throughout the growing-season. Consequently, whereas natural rainfall is likely merely to redistribute the water-soluble soil constituents, rice irrigation will tend to result in their complete removal from the soil in the drainage water.

Beside the special effects due to waterlogged conditions, rice irrigation may produce changes similar to ordinary irrigation methods. In practice the effects of irrigation due to a simple increase in the moisture supply are complicated by the composition of the irrigation water, particularly its salt content and cation balance. Thus the water-soluble salts of sodium, potassium, calcium, and magnesium, which are among the most mobile of the soil constituents and most likely to be removed by irrigation may be increased rather than diminished and the composition of the ions on the absorption complex may be markedly changed.

The Effect of Rice Irrigation on Soil Acidity

The pH of the soil samples, expressed as the means of the profiles from each cropping frequency, are given in Table 2. It can be seen from these figures that the difference in pH between the soils underlain by permeable and impermeable subsoils follows that which appeared in the virgin soils, i.e. over the impermeable subsoil the pH values are generally higher at all depths sampled. It would also appear at first sight that rice-growing over a period of 20 years has had no cumulative

TABLE 2

Mean pH of the Soil for Seven Rice-growing Treatments, compared with the Figures for Virgin Soil

Depth		0–4 in.		4–15 in.		15–30 in.		40–48 in.	
Subsoil		Permeable	Impermeable	Permeable	Impermeable	Permeable	Impermeable	Permeable	Impermeable
No. of rice crops	*No. of profiles*								
Virgin	6	5·17	5·28	6·73	7·08	7·68	7·81	7·71	7·80
1 rice crop	8	5·37	5·42	6·94	6·59	7·78	7·57	7·83	7·94
2 rice crops	8	4·98	5·30	6·58	6·62	7·74	7·74	7·85	7·89
3 " "	8	5·08	5·18	6·59	6·79	7·80	7·73	7·90	7·88
4 " "	8	4·79	5·60	6·77	6·69	7·69	7·60	7·76	7·77
5 " "	8	5·33	5·11	6·68	6·59	7·51	7·52	7·76	7·68
6 " "	8	4·74	5·09	6·19	6·87	7·44	7·67	7·68	7·87
7 " "	5	5·34	5·62	6·58	6·90	7·44	7·72	7·62	8·02
Mean of all rice-growing treatments		5·09	5·33	6·62	6·72	7·63	7·65	7·77	7·86

effect on the acidity of these soils, since at all depths sampled the mean of the pH figures of the different rice-growing treatments is scattered about the general mean of all the treatments, and there seems to be no relationship between the number of rice crops and the pH.

This lack of effect appears to be due to the fact that in any group of soils which have grown the crop, there are included soils which were last sown to rice at varying times during the last 10 years, and there may be a tendency for the pH of soils on which rice has not been grown for a number of years to return to that of the virgin soil. This effect can be seen by grouping the soils according to the length of time since the latest

TABLE 3

Relationship between Soil pH and Time since Latest Rice Crop

Time of sowing latest rice crop	1945	1944	1943	1942	1941	Virgin soil
No. of profiles over permeable subsoil	16	7	17	9	5	6
Average number of rice crops grown	4·94	4·71	4·12	3·89	2·40	..
Mean pH of soils over permeable subsoil at depths of						
0–4 in.	4·56	4·68	5·48	5·58	5·18	5·17
4–15 in.	6·06	6·46	6·64	6·70	6·56	6·73
15–30 in.	7·56	7·44	7·40	7·68	7·54	7·68
40–48 in.	7·64	7·60	7·56	7·88	7·82	7·71
Number of profiles over impermeable subsoil	12	7	15	11	5	6
Average number of rice crops grown	4·92	4·14	4·80	3·54	2·40	..
Mean pH of soils over impermeable subsoil at depths of						
0–4 in.	5·18	5·48	5·60	5·62	5·12	5·28
4–15 in.	6·64	6·76	6·74	6·86	6·80	7·08
15–30 in.	7·48	7·70	7·72	7·72	7·74	7·81
40–48 in.	7·82	7·92	7·92	7·88	7·80	7·80

rice crop. (The soils were sampled in August–September 1946, the last rice crop having been harvested about 3 months before.)

Grouped in this manner, the figures suggest that rice irrigation has a depressing effect on the pH which is most marked on the surface samples of the soils underlain by a permeable subsoil. Part of the effect shown, however, may be due to the larger number of rice crops that have been grown on those soils most recently under rice, as can be seen by comparing the figures for average number of rice crops grown for each time-group.

The Effect on the Chloride Content

The figures obtained for the chloride content of the virgin soils (Table 1) show a gradual increase through the first three horizons sampled, followed by a relatively sharp rise in the 40–48 in. sample. The chloride content of the lowest sample from all profiles was therefore determined, to measure the effect of the varying irrigation treatments used, and the means of the results are given in Table 4.

TABLE 4

Mean Chloride Content (mg./100 g. soil) of the 40–48 in. Horizon in Relation to the Number of Rice Crops

	Virgin soil	*Irrigated but never under rice*	*Number of rice crops*							
			1	*2*	*3*	*4*	*5*	*6*	*7*	*More than 7*
Profiles overlying permeable subsoil:										
No. of samples	6	5	10	8	8	8	8	8	5	3
Means	83	46	51	9	8	9	10	10	10	8
Profiles overlying impermeable subsoil:										
No. of samples	6	3	8	8	8	8	8	8	5	2
Means	70	37	12	12	16	18	25	14	8	9

Difference for significance at 5% level, 31·7 mg. per 100 g. } for a mean of six determinations
" " " " 1% " 49·7 " " " }
" " " " 5% " 25·3 " " " } for a mean of eight determinations.
" " " " 1% " 37·4 " " " }

It can be seen that the effect of the rice irrigation on soils overlying both permeable and impermeable subsoils is to lower the chloride content markedly and rapidly. For those sites overlying the permeable subsoil there is no further reduction in chloride after more than two rice crops, whilst for sites over impermeable subsoil, one rice crop is as effective as a greater number, in spite of the varying time intervals since the last rice crop was sown. There is no significant difference between the chloride content of the virgin sites over permeable and those over impermeable subsoils.

As for the pH, the effect on the chloride content can be considered in terms of the time since the last rice crop, and the means for the analyses grouped in this manner are given in Table 5.

TABLE 5

Relationship between Chloride Content of the 40–48 in. Horizon and the Time since Last Rice Crop

Time of sowing latest rice crop	*Over permeable subsoil*		*Over impermeable subsoil*	
	No. of samples	*Mean* Cl	*No. of samples*	*Mean* Cl
1945	16	14·1	12	8·2
1944	7	11·1	6	20·7
1943	17	17·7	15	13·6
1942	7	11·0	11	18·6
1941	5	34·6	4	9·5
1940 or earlier	6	31·6	7	13·9
Mean of all samples that had ever grown rice	58	18·0	55	14·0

Difference for significance between two means of 50 determinations, at the 5% level = 10·7 mg./100 g. soil.

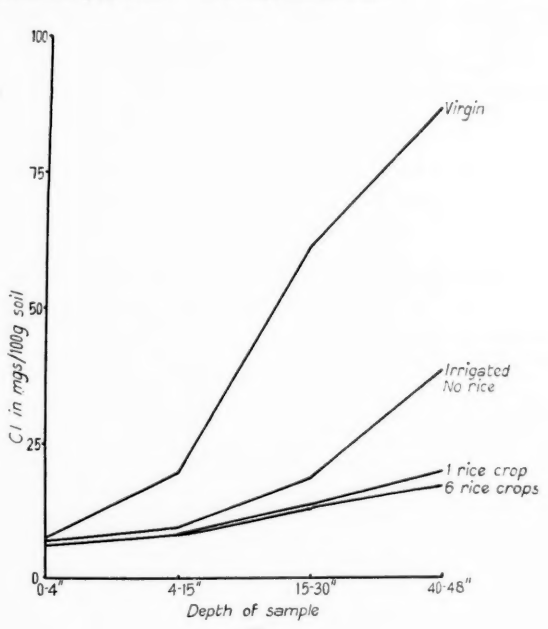

FIG. 1.

One rice crop has apparently a marked effect in leaching the chloride out of the soil, and there appears to be no tendency for it to increase to its former levels for at least a longer time-interval than has elapsed to date. For those soils which have grown rice, there is no significant

difference between the chloride content at the 40–48 in. layer of the soils over permeable and impermeable subsoils.

The growth of pastures or wheat under irrigation does not require the land to be flooded continuously throughout the growing-period, as does the growth of rice, and the leaching of chloride that takes place under such crops appears to be less intense than that under rice.

To investigate the effect on the upper horizons, four profiles were taken at random from each of the irrigation treatments and the results are shown in Fig. 1.

The Effect on the Sulphate Content

When these soils were first surveyed, when rice cultivation on the areas was in its infancy, gypsum crystals were commonly observed to be present, the gypsum horizon being encountered between 3 ft. 6 in. and 4 ft. deep (H. N. England, private communication).

During the field work of this study gypsum was generally much more difficult to detect, and in many cases could not be seen by the naked eye. Analysis of the samples supports the field evidence that gypsum has been leached from the soil.

The figures for virgin profiles (Table 1) show that there was no detectable sulphate in the upper three layers sampled. Consequently only the lowest sample from the other profiles was analysed and the mean values are shown in Table 6.

TABLE 6

Sulphate Content (mg./100 g. soil) of the 40–48 in. Horizon in relation to the Number of Rice Crops

	Virgin soil	*Irrigated but never under rice*	*Number of rice crops*						*Average of all soils*
			1	*2*	*3*	*4*	*5*	*6*	
Profiles overlying permeable subsoil:									
No. of samples	6	5	9	8	9	8	8	8	61
Means	303	87	211	118	47	63	37	38	109·3
Profiles overlying impermeable subsoil:									
No. of samples	6	3	8	8	8	8	8	8	57
Means	76	55	84	68	43	128	105	117	87·4

Difference for significance at the 5% level: for a mean of six = 188 mg./100 g.
" " " eight = 149 mg./100 g.

It appears that for sites overlying the permeable subsoil, rice-growing has resulted in a distinct lowering of the sulphate content of the 40–48 in. horizon, but the reduction requires a longer period than is needed for chloride and does not become significant until after four rice crops. The trend is thus similar to that shown by the figures for chlorides, but is modified in a manner that might be expected from the lower solubility of the sulphate ion. That is to say, a longer period under rice is required to leach sulphates even over permeable subsoils, whilst it is not yet

possible to show any leaching of sulphate from those soils overlying the impermeable subsoils.

The effect on the sulphate content can also be considered in terms of the time since the last rice crop.

TABLE 7

Relationship between the Sulphate Content (in mg. SO_4 per 100 g. soil) of the 40–48 in. Horizon and the Time since the Last Rice Crop (sampled 1946)

Time of sowing latest rice crop	*Over permeable subsoil*		*Over impermeable subsoil*	
	No. of samples	*Mean* SO_4	*No. of samples*	*Mean* SO_4
1945	11	80·2	10	32·9
1944	6	46·8	6	158·0
1943	15	90·5	10	39·9
1942	7	77·9	10	158·4
1941	5	53·2	5	151·0
1940 or earlier	5	196·6	7	43·9
Mean of all samples from sites that had grown rice	49	88·0	48	90·0

The lack of effect shown for the length of time since the last rice crop agrees with the result obtained above, namely that since the effect of rice irrigation in leaching sulphate out of the soil is cumulative over 4 or 5 years, it would not be expected that any return of the sulphate would occur over a time interval as short as five years.

The Effect on the Carbonate Content

The figures for carbonate content of the lower two horizons (III and IV) sampled from certain profiles are given in Table 8. The results show that there was no trend towards lower values with increasing frequencies of rice irrigation.

TABLE 8

Effect of Rice Irrigation on the Carbonate Content of Certain Profiles

Virgin		*Over permeable subsoils*										*Over impermeable subsoils*			
		1 rice crop		*2 rice crops*		*4 rice crops*		*6 rice crops*		*7 rice crops*		*1 rice crop*		*6 rice crops*	
III	*IV*	*III*	*IV*	*III*	*IV*	*III*	*IV*	*III*	*IV*	*III*	*IV*	*III*	*IV*	*III*	*IV*
0·2	1·2	1·3	0·2	1·1	1·1	5·4	2·8	0·2	0·7	0·6	1·2	0·0	1·6	0·6	0
4·9	2·0	0·3	0·9	1·2	1·3	1·7	1·3	1·1	1·8	0·6	1·8	0·8	0·7	0·7	0
4·5	2·8	1·6	0·9	4·5	1·6	0·7	0·6	3·1	2·2	2·8	0·8	1·5	2·0	1·0	0
1·2	0·2	0·1	0·4	0·9	1·0	1·1	1·1	0·2	1·3	0·4	0·0	2·2	2·8	4·3	1
0·1	0·7	0·5	0·6	1·0	0·5	2·4	2·0	0·6	1·1	2·8	0·5	2·7	1·2	2·8	4
0·9	0·6	1·2	2·1	1·3	2·9	2·7	2·3	1·9	2·1	..	..	1·8	1·0	2·8	2
..	..	0·7	0·7	0·6	3·0	2·9	1·7	1·4	1·2	..	..	0·7	0·5	2·3	1
..	..	2·3	1·5	6·1	3·1	0·5	0·6	1·8	1·2	..	..	0·2	0·0	0·4	1
Means															
III 1·96		1·16		2·10		2·16		1·29		1·44		1·28		1·8	
IV 1·25		1·06		1·81		1·55		1·45		0·86		1·10		1·4	

III = sample from 15 to 30 in. IV = sample from 40 to 48 in.

The Effect on the Organic Matter

Nitrogen was determined on nearly all of the surface soil samples (Table 9).

TABLE 9

Nitrogen Content (mg./100 g. soil) of the 0–4 in. Horizon

	Virgin soil	*Irrigated but never under rice*	*Number of rice crops*				
			1	*2*	*3*	*4*	*7*
Profiles overlying permeable subsoils							
Number of samples	6	5	9	8	9	8	5
Mean	102	101	117	122	105	116	103
Profiles overlying impermeable subsoils:							
Number of samples	6	3	8	8	7	7	5
Mean	105	164	104	98	114	105	108

The nitrogen content of the surface soils does not appear to have been influenced in any way by rice-growing; the nitrogen losses commonly associated with continuous cereal-growing have apparently been counterbalanced by the nitrogenous manuring that is practised with the rice crop, annual dressings of the order of 1 to 2 cwt. of sulphate of ammonia being normally used.

Organic carbon was determined on all virgin samples and a few others. The figures showed no consistent variation, but the C/N ratios of the soils are relatively constant, varying from 11·7 to 16·0, with a mean figure of 13·7.

The Effect on the Exchange Complex

Determinations were restricted to the surface layers of those soils which had carried six rice crops, and the averages of the results, together with those of the virgin soils, are given in Table 10.

TABLE 10

Effect of Rice Irrigation on the Exchangeable Cations of Surface Soil (0–4 in.)

	Exchangeable cations (m.e./100 g. soil)					*Exchange capacity*
	Ca	Mg	K	Na	*Total*	
Over permeable subsoil						
Six rice crops (5 samples)	9·18	5·22	0·39	0·48	15·27	26·7
Virgin soil (3 samples)	14·77	2·72	0·97	0·76	19·19	25·0
Over impermeable subsoil						
Six rice crops (5 samples)	8·10	4·95	0·72	0·80	14·57	25·8
Virgin soil (3 samples)	11·64	1·07	0·89	0·53	14·13	19·30
All irrigated soils	8·64	5·09	0·55	0·64	..	26·25
All virgin soils	13·20	1·90	0·93	0·64	..	22·30
All soils over permeable subsoil	11·04	4·99	0·58	0·57	..	26·1
All soils over impermeable subsoil	9·28	3·86	0·78	0·71	..	23·6

From these figures it appears that the exchangeable calcium figure has declined slightly both over the permeable and impermeable subsoils, and the proportion that it represents of the total bases has fallen quite markedly. This has been counterbalanced by a rise in the exchangeable magnesium, both in its absolute level and as a percentage of the total exchangeable bases.

The exchangeable sodium figures are erratic, and show no consistent trends, but the figures for exchangeable potassium show a distinct lowering both over the permeable and over the impermeable subsoils.

These changes may be explained in part by the cultivation practices and the nature of the irrigation water used. The inevitable practice in rice cultivation is to grade the country into a series of level bays. Since the original surface is markedly undulating, the grading and subsequent ploughing, &c., result in subsoil being exposed and subsequently mixed with what had been top soil. From Table I it can be seen that the subsoil is higher in magnesium and lower in potassium than the top soil. The incorporation of this material would consequently contribute to the higher magnesium and lower calcium shown by the soils that have carried rice.

The potassium content of the Murrumbidgee Irrigation water is so low that it has been neglected in all the analyses completed to date. The Murrumbidgee water contains on the average 0·45 m.e. of calcium, 0·40 m.e. of magnesium, and 0·35 m.e. of sodium (Table II) and these levels do not appear to disturb the relative levels of these ions on the exchange complex. The lack of potassium in the irrigation water appears to be associated with the leaching of potassium shown by the soils under rice, which is more marked in those soils overlying the permeable beds than it is for those overlying the impermeable beds. The soils at present do not show any response to potassium fertilizers, nor would any be expected at the level of exchangeable potassium found.

TABLE II

Composition of Irrigation Water (m.e. per litre), Murrumbidgee Irrigation Areas. Average Value for Season 1945–6 (supplied by N. G. Cassidy)

	Total soluble solids	*Calcium*	*Magnesium*	*Sodium*	*Bicarbonate*	*Chloride*	*Sulphate*
Average	85 p.p.m.	0·45	0·40	0·35	0·55	0·30	0·15
Range	63–120 p.p.m.	0·3–0·6	0·2–0·6	0·13–0·5	0·41–1·09	0·14–0·54	0·02–0·22

The increase in exchange capacity shown by the mean of the irrigated soils, compared with that for the unirrigated, is probably merely a further reflection of the incorporation of subsoil into top soil during the original grading of the land for rice cultivation.

The clay minerals appear to be principally hydrous micas, with a little montmorillonite in the deeper horizons (G. K. Robertson, private communication), which accounts for the relatively low exchange capacities shown by these heavy clay soils.

Discussion

From these results it does not appear that rice-growing has had any deleterious effects upon the soil, unless the acidification that has taken place on the soils overlying the permeable subsoils could be so considered. Since the irrigation water used on these areas has a favourable ionic balance (Cassidy, 1944) it is unlikely that rice irrigation will lead to the building up of excessive concentrations of sodium ion on the exchange complex. The loss of gypsum that has occurred in the soils overlying the permeable subsoils can hardly be considered to be detrimental since the principal effect of the loss might be to lower the permeability of the deep subsoil. As one of the main problems of rice-growing has been the excessively high water-consumption, by percolation of water through the soils and into the deep sand-beds that lie below, any reduction in the permeability of the subsoil would be more likely to be beneficial than otherwise. Current rice-production practices are clearly not causing any reduction in the nitrogen content of the surface soil, nor, on the other hand, are these soils showing the increase in nitrogen content with their improved moisture supply that would be expected from the application of the Jenny and Leonard equation (Jenny and Leonard, 1943). The presence of large amounts of hydrous mica in the clay fraction makes it unlikely that these soils will suffer from potassium deficiency for a prolonged period.

The effect of rice irrigation in leaching out the salt (NaCl) from even the deeper layers of the soil is particularly striking, and perhaps offers the best explanation of the beneficial effects that have been observed in the field. These results, when allied to field experience, suggest that rice could be used to advantage as a pioneer crop for the establishment of irrigated pastures. Two rice crops appear to be almost as effective as five or six in lowering the salt content of the entire profile, and are much more effective than several years of irrigation under other crops. One effect not shown by these results is the marked improvement in structure of the surface soil that can be seen immediately after a rice crop has been taken off the land. As well as the chemical effects of washing out the salt, the strong root-system developed by the rice crop has a vigorous granulating effect upon the surface soil. Although this effect is fleeting, and leaves no trace in a higher organic carbon content, even in the next year, it is important in providing for a few months the conditions required to obtain a good take of grass and clover seeds.

Pedogenically, the results obtained here afford evidence of the order of loss of certain soil constituents under leaching. Soluble chlorides are clearly the most mobile of the soil constituents, and are rapidly removed even from heavy soils underlain by impermeable subsoils. The presence of chlorides in a soil must consequently be taken as an indication of the leaching status of the soil at the present time, and cannot be considered as a relict feature of the profile.

Gypsum must also be in general an indicator of present pedogenic conditions. It moves fairly readily in these heavy soils, although it moves much less readily, if at all, where the soils have poor under-

drainage, that is to say, where they overlie impermeable beds. The presence of a gypseous horizon in high-rainfall areas could be expected, therefore, in profiles in which the underlying beds were sufficiently impermeable to prevent it from being leached through them.

Calcium carbonate, on the figures obtained here, is much less readily leached than are gypsum and the chlorides, and would thus be expected to persist in soils that were too strongly leached to retain either chlorides or gypsum. This has been postulated in soil classification for many years, but without experimental evidence from the soil itself.

The figures recorded for the pH of the surface soils are distinctly lower than might have been expected for soils that have developed under a semi-arid environment, and contrast markedly with the figures shown for the lower horizons, but are in accordance with the suggestion originally made by Howard (1939) that these soils are partly solodized. In this case the increased leaching due to rice irrigation has carried the solodization further than occurs in the virgin state, and the pH has fallen to lower values as a result. The absence of the effect from those profiles overlying the impermeable subsoil is thus a reflection of the smaller throughput of leaching waters that is shown by the records for water consumption for the areas concerned.

The low pH figures shown by these soils have been paralleled by those obtained in investigations in the Pilliga district and elsewhere in New South Wales, which will be the subject of a separate communication.

Summary

A study has been made of the changes in pH, chlorides, sulphates, organic matter, and the exchange complex that have followed the cultivation of rice on grey and brown gilgai soils in the Riverina district of New South Wales.

It has been shown that the effects produced vary both with the number of rice crops grown and with the nature of the underlying subsoil.

For those soils overlying permeable subsoils there has been a fall in the pH of the surface soil, and chlorides and sulphates have been leached out but carbonates have not been affected. Exchangeable potassium and sodium have also fallen, but no effect is seen on the organic matter.

For those soils overlying the impermeable subsoils there has been some leaching of chlorides, but the other effects shown by the soils over permeable subsoils are not demonstrable from these figures.

The significance of these findings is discussed from both the agronomic and pedogenic points of view.

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STUDIES IN PEDOGENESIS IN NEW SOUTH WALES

II. THE CHOCOLATE SOILS

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Introduction

In a recent paper on soil classification (Hallsworth and Costin, 1950) the soil groups known to occur in Australia were listed. Some of these groups have not yet been described in the literature. One such group, the soils developed on basalt under conditions of moderate temperature and rainfall, are of some extent and economic importance in New South Wales. To these soils the name 'chocolate basalt soils' was applied tentatively by one of the authors some time ago and has proved sufficiently useful to warrant further consideration.

A typical profile of the normal soil of this group would show a chocolate-coloured, friable clay loam surface soil, which is not self-mulching; this overlies a grey-brown to chocolate to reddish chocolate clay or clay loam at about 12 in. In the lower horizons the colour becomes flecked with greys, browns, and yellows, until the decomposing rock is encountered at from 2 ft. to 5 ft. or even deeper. Floaters of basalt are almost invariably present in the upper horizons, ranging in size from pebbles to quite large rocks. The soils are slightly acid at the surface, with the pH rising in the subsoil, but there is no horizon of calcium carbonate.

Extensive areas of these soils occur in New South Wales on the Monaro west and south-west of Cooma, and around Crookwell, on the Southern Tablelands; around Orange on the Central Tablelands; and around Guyra on the Northern Tablelands. They are found also as a minor component of the association of soils formed on basalt throughout the Namoi region as far west as Yallaroi and Bellata (Gibbons and Hallsworth, 1951), on the Liverpool, Nandewar, and Warrumbungle ranges, and in the hills and ranges along the upper Richmond River valley on the north coast.

Status

Observation of these soils in the western and drier areas of the State might suggest that they could be classified as skeletal soils, but this not only would obscure their position in the climatic sequence but would not allow for the deep profiles commonly found in the type localities. To describe them as immature soils derived from basalt is also unsatisfactory, since it would be equally correct to describe by the same term the chernozem-like soils of the Inverell and Warialda districts. On the other hand, adopting the concept of Jenny (1941) that a soil is a function of the four main soil-forming factors, parent material, climate, topography, and organisms, and of the time during which they have operated, then it

follows that the chocolate soils are that group of soils the existence of which could have been predicted from a knowledge of the conditions under which the krasnozems (acid red loams) and chernozems have been formed.

Thus in the conditions under which the krasnozems have been formed from basalt as parent material, the rate of leaching is sufficiently intense largely to remove the exchangeable mono- and divalent bases from the soil as rapidly as they are released, even under rapid weathering conditions. At the same time silica has been lost, so that the SiO_2/R_2O_3 ratio, whether measured on the whole soil or on the clay fraction only, shows a marked fall when compared with that of the parent rock. Because of the finely crystalline nature of the parent material, the derived soil contains insufficient sand to allow texture differentiation. The krasnozems developed on basalt thus show on analysis a relatively high clay content throughout the profile. Because the exchange complex is largely saturated with the trivalent ferric and aluminium ions and with hydrogen, a low pH results. The whole soil is well aggregated into small fine crumbs, with a red colour.

On the other hand, under the conditions under which the chernozems have been formed from basalt, the leaching has been much less drastic, the exchangeable mono- and divalent bases being largely retained and saturating the exchange complex. Sufficiently high concentrations of exchangeable calcium have developed in the subsoil to allow the deposition of free calcium carbonate. Under such conditions the rate of loss of silica has been low, and the SiO_2/R_2O_3 ratio is consequently high. Chernozems derived from basalt show a high clay content throughout the profile, as do the krasnozems. Because the exchange complex is largely saturated with the mono- and divalent bases a fairly high pH results, with the surface soil a black or dark brown colour and possessing a good crumb structure, the aggregates being slightly larger than in the krasnozems, and showing the appearance in the field commonly called 'self-mulching'.

In situations where the weathering conditions are intermediate between those under which the krasnozems and the chernozems develop, the soils developed might be expected to be intermediate in character. In such soils the rate of removal of the bases would be less than in the krasnozems but greater than in the chernozems; thus it may be expected that the exchange complex would contain a greater proportion of the mono- and divalent bases and a smaller proportion of hydrogen than would the krasnozems. The concentration of exchangeable calcium, however, need not be so high as to allow the formation of an horizon of calcium carbonate. The soil, being derived from basalt, would still show a relatively high clay content throughout the profile. Since the soil would contain neither the highly sesquioxidic clay nor free calcium carbonate, the degree of structure development manifest by the surface soil would not be so great as that shown by the groups of soils developed in either more or less strongly leaching environments. The nature of the cations saturating the exchange complex would result in the pH of the soil being intermediate between that of the chernozems and that of the

krasnozems. The colour of the krasnozems is red, due to the dominance of the trivalent cations on the exchange complex, and the subsequent formation of free iron oxides, whilst the colour of the chernozems is black or dark brown, due to the saturation of the organic colloids with calcium. It might be expected that, for the chocolate soils, of which the exchange complex is saturated with neither iron nor calcium, a colour would be developed dominated by the normal colour of humus, namely, some shade of brown.

The chocolate soils as they have been observed in New South Wales on basalt form a definite stage in the sequence of profile development too distinct from both the chernozems and the krasnozems to be adequately described as transitional soils. The alternative of regarding them as 'immature' krasnozems or 'immature' chernozems would not only confuse, but also lessen, the usefulness of those groupings. Whether they be considered in terms of profile features, of conditions of formation, of associated vegetation, or of cultural and fertility properties, it would appear to be necessary to recognize their existence as a separate group. Theoretically they could also develop on other fine-grained basic rocks, such as dolerite or calcareous shales or mudstones.

Relation to Topography and Climate

It is not possible to describe the soils adequately without reference to the position on the catena in which they occur.

In the type areas of Orange, Guyra, and Crookwell, where the soils reach their maximum development, they occupy most of the positions on the catena. At these localities the mean minimum temperatures range from 40 to 43° F. and the mean maximum temperatures from 64 to 66° F. The mean annual rainfall for the three centres is from 33 to 36 in. On the Monaro, with lower winter temperatures, they extend widely through areas of much lower rainfall.

Two sub-groups may be recognized in addition to the normal chocolate soils. These are (*a*) the reddish chocolate soils, and (*b*) the grey chocolate soils.

The climatic data for certain localities are given in Table 1.

Precisely which positions on the catena are occupied by the chocolate soils is dependent on climate, the effect of rainfall being affected by the temperature.

Under low rainfalls (17–25 in.) and moderate temperatures as at Cooma, the reddish chocolate soils occupy the upper part of the catena, with normal chocolate soils on the middle slopes; then a belt of prairie soils below, giving way to chernozems and occasionally sierozem in the lowest positions. At higher temperatures (Namoi region) the reddish chocolate soil occupies progressively smaller parts of the crest of the slope, and the normal chocolate soil is restricted to a narrow band or may disappear completely. Its place, and that of the prairie soil, is taken by brown chernozem-like soil which occupies the middle and lower slopes, and is succeeded by black chernozem-like soils and occasionally sierozem-like soils on the lowest parts.

Under moderate rainfalls (25–35 in.) and colder temperatures as

TABLE 1

Climatic Data for Certain Localities in which Chocolate Soils are developed on Basalt, with Comparative Figures from Chernozem and Krasnozem Areas. (Taken from C.S.I.R.O. Pamphlet No. 42, 1933)

Locality	*Cooma*	*Bellata*	*Inverell**	*Glen Innes*	*Guyra*	*Orange*	*Crookwell*	*Dorrigo†*	*Nimmitabel†*
Soil type(s)	Chocolate and Chernozem	Chocolate and Chernozem	Chocolate and Chernozem	Chocolate and Prairie Soil	Chocolate	Chocolate	Chocolate	Krasnozem	Grey Chocolate and Prairie Soil
Normal mean maximum temperature	67·7	80·4	74·5	68·3	64·6	65·9	64·6	71·8	59·9
Normal mean minimum temperature	40·5	52·8	44·7	43·9	40·9	43·0	41·3	47·4	38·0
Average annual precipitation	18·77	24·0	29·94	31·30	34·89	34·54	32·67	73·61	26·87
					Type areas				

* The red soils overlying basalt that also occur in the Inverell district have been found to be associated with lateritic residuals. This has formed the subject of a separate investigation, and will be reported elsewhere.

† Figures obtained by courtesy of Meteorological Bureau, Sydney.

occur on the divide east of Nimmitabel (Monaro), at Ebor (New England), or Oberon (Central Tablelands), the normal and reddish chocolate soils are replaced by grey chocolate soils, with prairie and meadow soils in the lower positions.

At moderate temperatures, in the type areas of Guyra, Orange, and Crookwell, normal chocolate soils predominate on the upper and middle portions of the slope, with occasional patches of reddish chocolate in the higher portions. Grey chocolate soils may be found on the lower slopes, with prairie or meadow soils on the flat areas.

With high temperatures, as in New England around Inverell, both black and brown chernozem-like soils occupy most of the catena, with chocolate and reddish chocolate soils in restricted portions at the top of the catena.

Under higher rainfalls (35–50 in.) the chocolate soils occupy progressively smaller portions of the catena, and above 55 in. they are almost completely absent, except for odd patches in the higher temperature areas where vigorous erosion has taken place. With high rainfall and low temperatures, as at Kiandra, alpine humus soils occupy all except the lowest parts of the catena, which carry bog soils.

With high rainfalls and moderate temperatures, as near Nimmitabel and at Mount Darragh on the Monaro, at Robertson on the Southern Tablelands, or at Dorrigo in New England, krasnozems occupy all parts of the catena except the lowest where occasional patches of prairie or meadow soils may be found.

With high rainfalls and high temperatures, as occur on the Northern Rivers of New South Wales, three different catenas occur, in zones depending on the rainfall. Where the rainfall lies between 35–50 in., as at Canaiba, or north and west of Kyogle, the normal chocolate soils generally occupy the steepest slopes, with prairie and chernozem soils on the flats and gentle slopes.

With rainfalls between 50 and 55 in., as occur on either side of a line from Nimbin to Lismore, the reddish chocolate soil no longer occupies the upper catenary position, which instead is occupied by krasnozem or transitional krasnozem, which gives way to normal chocolate soils over the major portion of the slope, with prairie soils on the flats at the bottom.

With rainfalls greater than 55 in., as occur from Alstonville to Bangalow, krasnozems occupy all positions of the catena, even the flats along the valleys, as can be seen on the middle reaches of Wilson's Creek.

It appears doubtful whether the reddish chocolate soil occurs at all in these higher rainfall areas.

Profile Characteristics of Chocolate Soils

The chocolate soil developing on basalt may be considered conveniently in three sub-groups:

(*a*) reddish chocolate soils;
(*b*) normal chocolate soils;
(*c*) grey chocolate soils.

Detailed morphological and analytical data (Tables 2 and 3) are given below.

Morphological Characters

(*a*) *Reddish chocolate soil*

I. *Cooma profile* (Profile No. N3)

Locality	Monaro, 1 mile east of Cooma on the Nimmitabel road, on top of the ridge.
Rainfall	18 in., with a cold winter.
A_0	Usually lacking, or where present, consisting of sparse grass litter.
0″–7″	Reddish chocolate clay loam; occasional basalt floaters; good crumb structure; porous and friable to slightly compact; humus moderate in amount and grass roots fairly abundant.
7″–11″	Reddish chocolate clay loam; occasional basalt floaters; crumb to nutty structure; finely porous and slightly friable to compact; little humus, but grass roots fairly abundant.
11″–25″	Reddish clay loam to light clay; occasional basalt floaters; crumb to nutty structures; fine porous to closed and compact to slightly tenacious; no visible humus and few grass roots.
25″–33″	Reddish light clay, passing into decomposing basalt parent material; basalt floaters and fragments of decomposing parent material abundant; crumb to nutty structure; closed, compact to tenacious; no visible humus and few grass roots.

II. *Mooki profile* (Profile No. 320)

Locality	New England, near Mooki Creek, 10 miles south-west of Pine Ridge on the Blackville road, and 25 miles west of Quirindi.
Rainfall	23 in., with a hot summer.
A_0	Usually lacking, or where present, consisting of grass litter.
0″–6″	Chocolate light clay loam; loose, hard crumb structure; porous and friable; humus moderate, grass roots abundant.
6″–12″	Reddish chocolate clay loam; loose, hard crumb structure; porous and friable.
12″–18″	Reddish chocolate clay; hard, crumb to cloddy structure; no visible humus.
18″–36″	Bright red chocolate clay; hard, cloddy structure; decomposing basalt pebbles; merging into decomposing basalt at 3 ft.

(*b*) *Normal chocolate soil*

I. *Cooma profile* (Profile No. N4)

Locality	In catenary association with the previous Cooma profile, and lower down the slope.
Rainfall	18 in., with a cold winter.
A_0	Usually lacking, or where present, consisting of sparse grass litter.
0″–11″	Dark chocolate clay loam; occasional basalt floaters; excellent crumb structure; porous and friable; humus and grass roots abundant; occasional earthworms.
11″–22″	Dark chocolate clay loam; occasional basalt floaters; fine crumb structure; fine porous to slightly compact; humus and grass roots fairly abundant; occasional earthworms.
22″–28″	Light chocolate clay loam to light clay; occasional basalt floaters; crumb to granular structure; almost closed and compact; humus and grass roots moderate in amount.
28″–33″	Light chocolate to yellowish chocolate, clay loam, passing into decomposing basalt parent material; basalt floaters and fragments of decomposing parent material abundant; crumb to nutty structure; closed and compact to tenacious; little humus and few grass roots.

II. *Molong profile* (Profile No. 38)

Locality	Central Tablelands, 3 miles east of Molong on the Orange road, on the lower slopes.
Rainfall	28 in. with moderate temperature.
0″–3″	Very dark chocolate-brown clay loam; crumb structure.
3″–15″	Dark chocolate-brown clay loam; crumb structure, somewhat friable.
15″–48″	Chocolate clay; cloddy structure; somewhat stiff at the top, becoming increasingly stiff with depth, compact.
48″–72″	Brown silty clay; decomposing basalt pebbles; merging into decomposing basalt at 6 feet.

III. *Guyra profile* (Profile No. 406)

Locality	New England, 5 miles south of Guyra on the Armidale road, on the middle slope.
Rainfall	35 in., with moderate temperature.
A_0	Lacking here, elsewhere if present, is a thin mat of grass litter.
0″–3″	Dark brown light clay loam; good coarse crumb structure; porous and friable.
3″–12″	Chocolate-brown clay loam; coarse crumb structure; slightly porous, friable at the top, but becoming more compact towards the bottom of the horizon; some pebbles.
12″–18″	Brown clay; structureless, closed and tenacious; pebbles present.
18″–30″	Brown clay; slightly stiff; khaki-coloured decomposing basalt entering at 24 in. and increasing in quantity to the parent material at 30 in.

(*c*) *Grey chocolate soil*

I. *Nimmitabel profile* (Profile No. N9)

Locality	Monaro, on the Monaro divide, 2 miles west of Nimmitabel on the Cooma road.
Rainfall	27 in., with a cold winter.
A_0, 0″–½″	Brownish black; decomposing grass litter.
½″–9″	Grey-chocolate to almost black light clay; occasional basalt floaters; excellent crumb to nutty structure; fine porous to slightly closed; friable to slightly compact; humus and grass roots very abundant; earthworms abundant.
9″–15″	Greyish chocolate medium to heavy clay; occasional basalt floaters; crumb to small cloddy structure; almost closed and compact; humus and grass roots abundant; earthworms abundant.
15″–20″	Yellowish chocolate medium clay; occasional basalt floaters; small cloddy structure; closed and compact to tenacious; little visible humus, but grass roots fairly abundant.
20″–30″	Yellowish brown clay loam, passing into decomposing basalt parent material; basalt floaters and fragments of decomposing parent material abundant; structureless; closed and tenacious; no visible humus and very few grass roots.

II. *Ebor profile* (Profile No. E1)

Locality	New England, 5 miles west of Ebor on the Guyra road, on middle slopes.
Rainfall	41 in., with moderate temperature.
A_0	Decomposing grass litter.
0″–6″	Very dark brown clay loam; good crumb structure.
6″–12″	Greyish chocolate clay loam; small cloddy structure; some basalt pebbles.
12″–24″	Dark greyish chocolate light clay; small cloddy structure; compact; some pebbles.
24″–32″	Greyish chocolate light clay; decomposing basalt pebbles; structureless.

TABLE 2

Locality	*Soil No.*	*pH*	*Depth*	*Coarse sand %*	*Fine sand %*	*Silt %*	*Clay %*	*Organic carbon %*
Reddish chocolate soils								
Cooma . .	N3.1	6·05	0–7″	56·9		14·3	28·8	1·61
	N3.2	6·20	7–11″	52·0		13·5	24·5	1·12
	N3.3	6·37	11–25″	48·2		18·0	33·8	0·94
	N3.4	6·75	25–33″	42·1		16·6	41·3	0·61
Mooki . .	320.1	5·80	0–3″	..	..	..	..	2·52
	320·2	5·85	3–6″	..	..	..	..	1·95
	320.3	6·15	6–12″	..	..	..	..	1·19
	320.4	6·20	12–18″	..	..	..	..	0·93
	320.5	6·20	18–24″	..	..	..	..	0·86
Normal chocolate soils								
Cooma . .	N4.1	6·20	0–11″	50·8		19·2	30·0	1·26
	N4.2	6·40	11–22″	48·0		22·7	29·3	0·97
	N4.3	6·65	22–33″	48·1		17·9	34·0	0·52
Molong .	38·1	5·7	0–3″	11·61	28·9	10·0	51·9	2·19
	38.2	5·45	3–15″	15·9	29·7	17·4	36·6	0·95
	38.3	6·10	15–24″	10·4	23·7	10·9	58·6	0·76
	38.4	6·65	24–42″	10·5	32·6	13·2	48·4	0·48
	38·5	7·20	42–48″	7·5	38·2	12·5	45·6	0·32
	38.6	7·30	48–60″	12·3	37·8	11·3	41·8	0·25
	38.7	7·25	60–72″	16·2	35·2	11·4	40·0	0·28
Guyra . .	406.1	6·3	0–3″	27·8	17·9	19·5	38·6	2·30
	406.2	6·3	3–6″	16·2	20·3	23·2	44·3	1·28
	406.3	6·3	6–12″	13·2	22·0	24·5	43·1	0·66
	406.4	6·3	12–18″	13·2	25·3	21·2	35·3	0·26
	406.5	..	18–24″	12·2	28·0	20·4	37·5	0·33
	406.6	6·8	24–30″	..	..	..	..	..
Grey chocolate soils								
Nimmitabel .	N9.1	6·00	½–9″	34·9		25·1	40·0	2·56
	N9.2	5·55	9–15″	20·5		17·7	61·8	1·53
	N9.3	5·70	15–20″	34·6		16·5	48·9	1·13
	N9.4	6·05	20–30″	62·2		9·9	27·9	0·69
Ebor . .	E1.1	5·1	0–9″	24·0		23·1	52·9	2·88
	E1.2	5·4	9–16″	25·4		22·8	51·8	1·90
	E1.3	5·6	16–24″	30·6		20·4	49·1	1·40
	E1.4	6·7	24–30″	42·5		18·4	39·2	0·71

Pedogenically related Great Soil Groups

The chocolate soil group has been grouped with prairie soils, brown earths, rendzinas, terra rossas, and brown soils of light texture as: 'Soils in which the profile shows no eluviation of sesquioxides. Slightly acid to neutral in the surface' (Hallsworth and Costin, 1950).

In general the relative abundance of montmorillonitic clay, the resultant high exchange capacity, and the characteristic subsoil constitution of the

TABLE 3

Soil No.	Depth	Exchangeable cations*					Total exchange bases*	Exchange capacity*
		Ca	Mg	K	Na	H		
N3.1	0–7″	11·64	15·82	0·61	0·44	0·33	28·51	28·84
N3.3	11–25″	25·87	11·02	0·10	0·62	0·23	37·61	37·84
N4.1	0–11″	16·22	11·04	0·08	0·59	1·80	27·93	29·73
N4.3	22–33″	14·50	16·17	0·10	0·99	1·20	31·76	32·96
N9.1	½–9″	21·75	15·89	0·01	0·12	2·53	37·77	40·30
N9.3	15–20″	38·37	21·20	0·02	0·26	7·22	59·85	67·07

* m.e./100 g. soil.

chocolate soil group are the most important diagnostic features which readily distinguish it from other above-mentioned pedogenically related great soil groups. Among these groups, only the prairie soils regularly possess a montmorillonite content and exchange capacity of the same order as the chocolate soils. The subsoil consitution is equally distinctive: the visible porosity being closed or only slightly fine-porous, and the handling consistency compact or tenacious.

Other differences between the chocolate and prairie soils are the self-mulching topsoil and the usually higher organic matter content of the latter group.

Rendzinas and terra rossas are, characteristically, associated with limestone rocks, and are further distinguished by their typically shallow and abrupt A–C type profiles without any gradual change, such as shown in chocolate soils, from subsoil to decomposing rock.

Brown soils of light texture are the analogues of reddish chocolate soils on coarser textured, more acid rocks, and are distinguished from them by their lighter texture, inferior crumb structure, much lower exchange capacity, and lower organic matter content.

The brown earths are the most closely related soil group, and in the broadest usage of the term (Robinson, 1936; Russell, 1937) would include the soils described above. Such usage allows the inclusion under the one heading of soils varying widely in clay content and probably in the clay minerals present (Russell, 1937, p. 180), which inevitably limits its value in soil mapping and classification, ecology, and agronomy.

It is suggested that the chocolate soils, as described above, may be separated validly as a great soil group differing from the brown earths in the higher exchange capacity, subsoil constitution, heavier texture, and greater abundance of montmorillonite. The authors would restrict the term brown earth to the four sub-groups brown forest soil, brown meadow soil, colluvial brown earth, and brown limestone soil.

Relationships with Associated Soil Groups

The relationship of soils developed on basalt to climate and topography has been presented already in a generalized form. It may be illustrated by the results from individual localities.

(*a*) *Climatic sequences.* The soils in these sequences occur on similar catenary positions (the middle slopes) and differ only in the climatic factor. They include chernozems or chernozem-like soils, chocolate soils, krasnozems, and alpine humus soils. Organic carbon and pH for such climatic sequences from both the Monaro and New England regions are shown in Figs. 1 to 4.

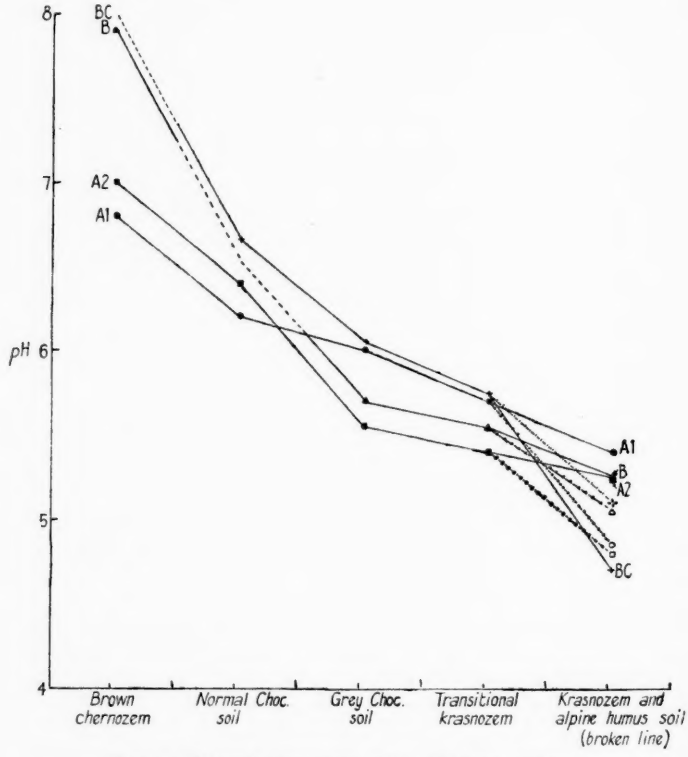

FIG. 1. Climatic sequence: pH. Monaro region.

For both regions there is a general increase in the organic carbon content of the surface horizons with increasing precipitation. It is noticeable also that in both sequences the surface soil of the krasnozems, despite its red colour, is distinctly richer in organic carbon than the chocolate soils. An exception to the general trend, shown on the graph for the Monaro region, is the slight decline in organic carbon for the transitional krasnozem. This is probably due to the 'organisms' factor, exhibited as a pronounced change in vegetation occurring under the particular climatic conditions. Savannah woodland with a dense grass cover characterizes the grey chocolate soils, and luxuriant wet sclerophyll forest characterizes the krasnozems, but the vegetation of the transitional

krasnozems is intermediate in character, consisting of an open forest with a sparse grass cover. Under these conditions, the accumulation of organic matter appears to be less. The effect of sub-alpine conditions, in particular increased cold and prolonged winter snow cover, is illustrated by the Monaro sequence, where the organic matter content of the alpine humus soil is considerably greater than that of the krasnozem.

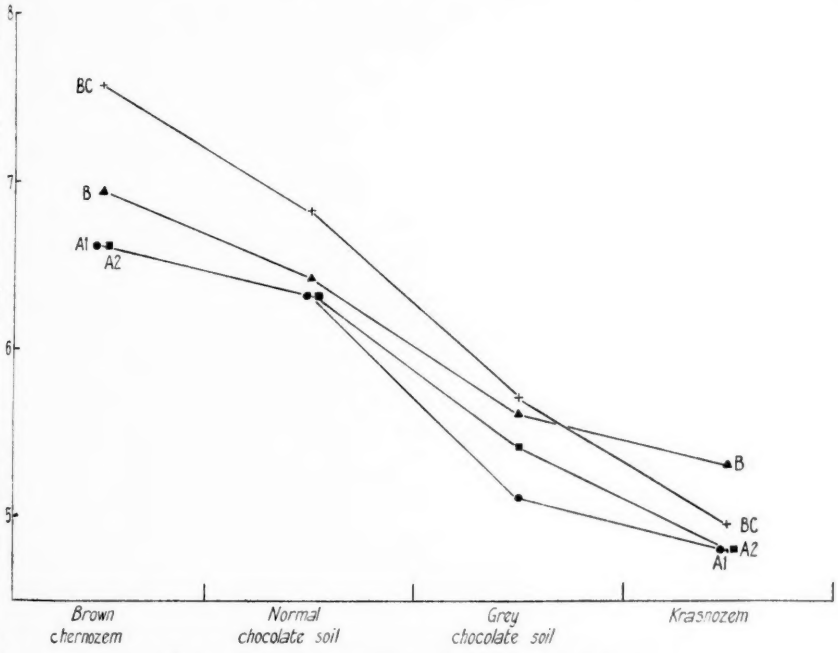

FIG. 2. Climatic sequence: pH. New England.

In both regions there is a general decrease in pH with increasing precipitation. For the drier members, brown chernozem and normal chocolate soil, the pH increases with depth, but for the moister members, grey chocolate soil, krasnozem, and alpine humus soil, the pH of the surface soil is higher than that of the immediate subsoil. This increased surface pH is probably due to the return of bases to the surface by leaf litter, with earthworm activity as a contributory cause.

(*b*) *Topographic sequences.* The soils in these sequences occur in similar climates, and differ only in their catenary position.

i. *The Cooma catena.* On the Monaro, 1 mile east of Cooma on the Nimmitabel road, the catena includes reddish chocolate soil (N3), normal chocolate soil (N4), prairie soil (N5), black chernozem (N6), and grey sierozem (N2), as in Fig. 5.

The outstanding feature of this catena is the presence, within a distance of 500 yards, of three members (reddish chocolate, normal

chocolate, and prairie soil) which are devoid of secondary calcium carbonate; of one member (black chernozem) in which the subsoil contains secondary calcium carbonate; and of one member (grey sierozem) in which secondary carbonate occurs almost to the surface, with gypsum in the deeper layers. The pH relationships of these soils are shown in Fig. 6.

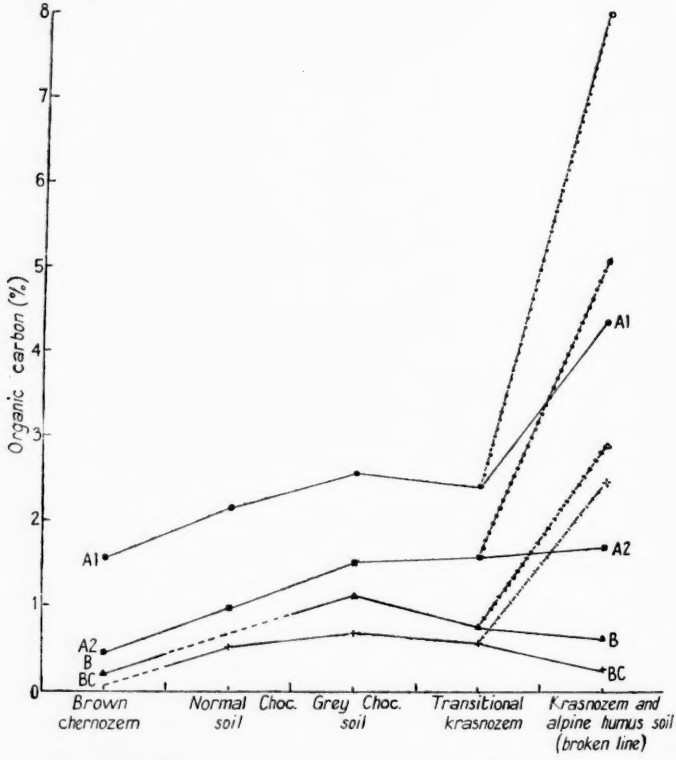

FIG. 3. Climatic sequence: organic carbon. Monaro region.

There is a general increase in pH with depth in each profile, and also a general increase in pH with descending catenary position. An exception to this is the lower pH of the BC horizon of the grey sierozems due to the fact that this sample was taken below the zone of maximum carbonate accumulation, whereas the BC sample for the black chernozem happened to fall within this zone.

ii. *The Mooki catena.* In the New England region, at Mooki, 10 miles south-west of Pine Ridge on the Blackville road, and 25 miles west of Quirindi, the catena includes reddish chocolate soil, normal chocolate soil, brown chernozem-like soil, and black chernozem-like soil, the latter two soils showing gilgai features, as in Fig. 7.

This catena is similar to that described from Cooma in that the sequence is from members (reddish chocolate and normal chocolate)

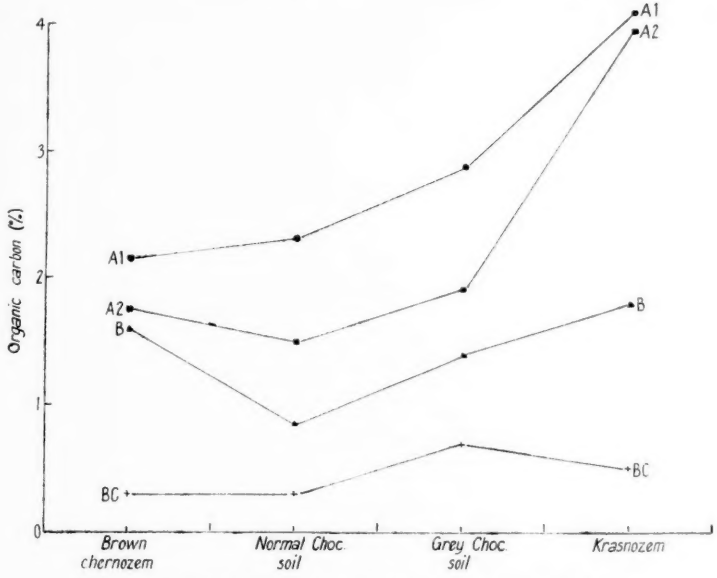

FIG. 4. Climatic sequence: organic carbon. New England.

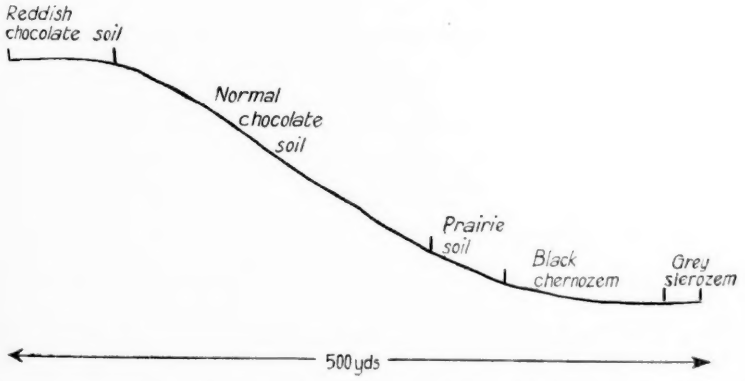

FIG. 5. Topographic sequence: Cooma, Monara.

devoid of secondary calcium carbonate and self-mulching characters to members (brown chernozem-like and black chernozem-like soil) which show these characters, the extent of the sequence being approximately 300 yards; it differs from the Cooma catena in that it shows the

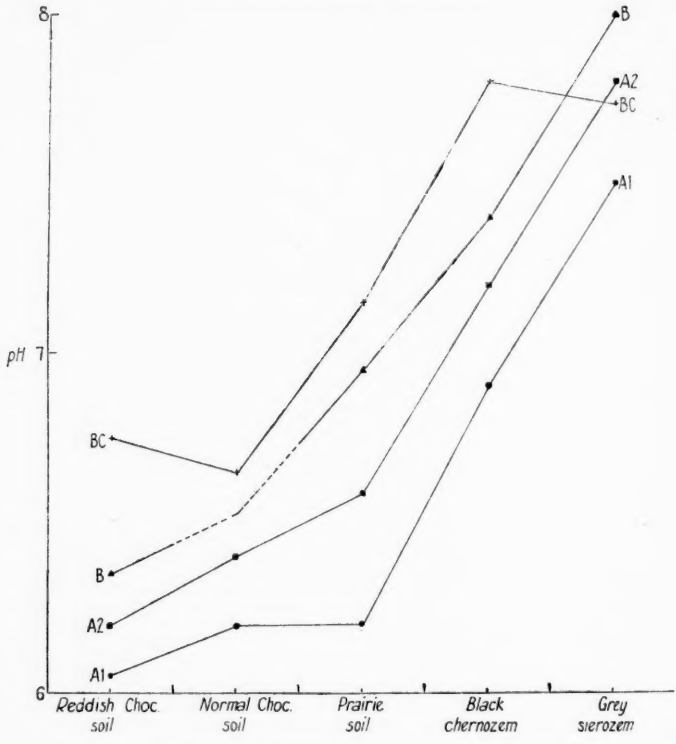

FIG. 6. Topographic sequence: pH. Monaro region.

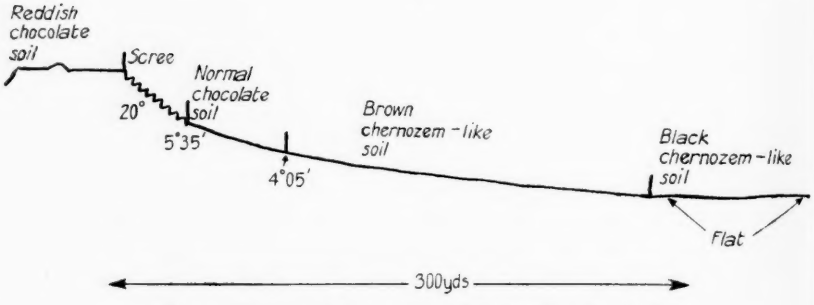

FIG. 7. Topographic sequence: Mooki, New England.

features of a less leaching climate in the replacement of the prairie soil by a brown chernozem-like soil; also, it does not include the extreme bottom member, the grey sierozem-like soil. The pH relationships of these soils are shown in Fig. 8.

There is a general increase in pH with depth in each profile, and also a general increase in pH with descending catenary position.

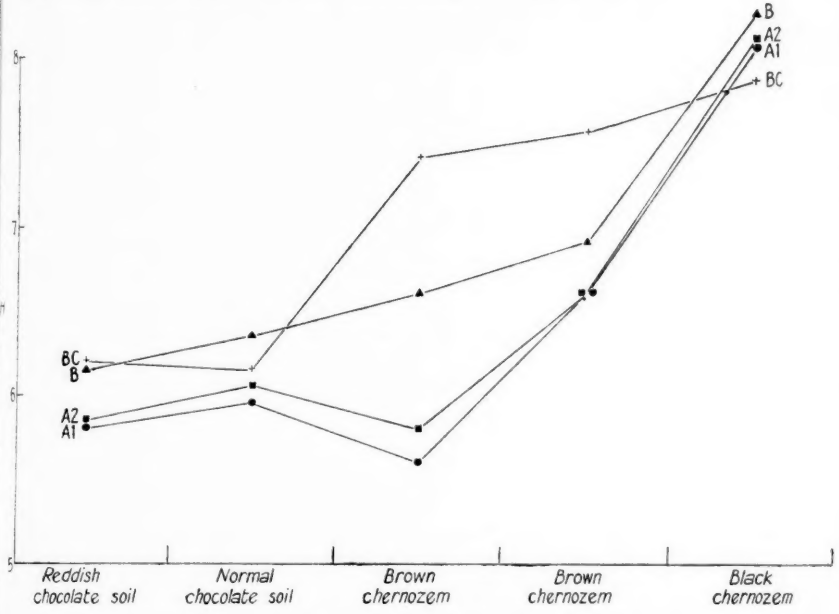

FIG. 8. Topographic sequence: pH. New England.

The Clay Minerals of the Chocolate Soils and Related Groups

A study of the clay mineralogy of the chocolate soils emphasizes their intermediate position between krasnozem and chernozem, and throws some light on the sharpness of the transition observed between the chocolate/chernozem catena and the krasnozem catena.

From Table 4 it can be seen that the clays of the chernozem soils derived from basalt are mainly composed of montmorillonite with smaller amounts of kaolinite in the approximate ratio of 4 or 5 to 1. Traces of quartz and illite are occasionally shown.

The reddish chocolate soils exhibit the same general picture, except that they contain rather more kaolinite. For the samples examined by thermal analysis, which are subsoil samples, the proportion is about 2 to 1. The normal chocolate soils show a distinct fall in the level of montmorillonite and a corresponding rise in illite, kaolinite remaining at much the same figure. The sample of grey chocolate soil examined links the chocolate soils to the transitional krasnozem, for while montmorillonite remains at the same figure, illite is no longer present, having been replaced by kaolinite, which in both soil groups is the dominant clay mineral.

TABLE 4

Results of X-ray and Thermal Analyses of Clays from some Chocolate and Related Soils

Soil No.	Depth	Locality	X-ray analysis: Montmorillonite	X-ray analysis: Kaolinite	X-ray analysis: Illite	X-ray analysis: Others	Thermal analysis: Montmorillonite	Thermal analysis: Kaolinite	Thermal analysis: Illite (by diff.)	Thermal analysis: Others
		Chernozem (Black)					%	%	%	
45·1	0–4″	Breeza, Liverpool Plains	+++	+	..	Quartz	63	25	12*	..
45.7	5–6′	,,	+++	+	..	Quartz	79	23	..	..
45.8	6–7′	,,	n.d.	n.d.	n.d.	n.d.	73	26	..	..
35429	5–6′	Prairie Vale, Inverell	+++	+	..	..	67	22	11	..
354b7	5–6′	,,	n.d.	n.d.	n.d.	n.d.	83	19	..	..
47.1	0–8″	Nea, Liverpool Plains	++++	+	..	Quartz	70	28	..	..
83.1	0–3″	Jincumbilly, Monaro	+++	..	trace	..	n.d.	n.d.	n.d.	n.d.
83.6	3–4′	,,	++++	..	trace	..	n.d.	n.d.	n.d.	n.d.
187.5	2–3′	Warialda	++++	+	..	..	65	37	..	..
		Chernozem (Brown)								
84.1	0–3″	Jincumbilly, Monaro	+++	..	+	..	n.d.	n.d.	n.d.	n.d.
84.8	5–6′	,,	+++	..	..	..	83	17	..	..
352.7	2′ 6″–3′ 0″	Prairie Vale, Inverell	+++	++	++	Quartz	86	27	..	..
		Reddish chocolate								
N3.4	25–33″	Cooma	++++	+	..	..	89	29	..	Iron oxide
N17.4	25–36″	Middle Flat, nr. Cooma	+++	+	..	..	62	38	..	..
320.5	18–24″	Mooki, nr. Quirindi	+++	+	..	Haematite	50	36	..	Iron oxide
		Normal chocolate								

320.5	18–24″	Mooki, nr. Quirindi	+++	+	..	Haematite	50	36	..	Iron oxide
		Normal chocolate								
406.1	0–3″	Guyra	++	..	++	..	n.d.	n.d.	n.d.	n.d.
406.4	12–18″	,,	++	++	++	..	25	28	47	..
38·1	0–4″	Molong	+	++	+++	Quartz	n.d.	n.d.	n.d.	n.d.
38.7	5–6′	,,	++	++	++	..	18	..	..	..
350.6	2–3′	Prairie Vale, Inverell	+++	+	..	..	54	27	..	..
82.1	0–3″	Maffra, Monaro	++	++	++	..	n.d.	n.d.	n.d.	n.d.
82.3	6–12″	,,	++	++	++	..	22	33	45	..
85.2	3–6″	Jincumbilly, Monaro	+++	..	+	..	n.d.	n.d.	n.d.	n.d.
85.6	3–4′	,,	+++	..	trace	..	n.d.	n.d.	n.d.	n.d.
		Grey chocolate								
E1.4	24–30″	Ebor, New England	n.d.	n.d.	n.d.	n.d.	26	70	n.d.	Iron oxide
		Transitional krasnozem								
N45.4	20–30″	Cathcart, Monaro	n.d.	n.d.	n.d.	n.d.	38	62	..	Iron oxide†
N16.1	0–6″	Nimmitabel, Monaro	n.d.	n.d.	n.d.	n.d.	24	41	n.d.	..
N16.4	21–26″	,,	n.d.	n.d.	n.d.	n.d.	80	20	..	..
		Krasnozems								
410.1	0–3″	Dorrigo	..	+++	..	Goethite Haematite Gibbsite	..	54	n.d.	Gibbsite
412.8	5–6′	,,	..	+++	..	Gibbsite	..	50	n.d.	Gibbsite
18.2	4–12″	Mt. Darragh	n.d.	n.d.	n.d.	n.d.	..	56	n.d.	Gibbsite

The X-ray photographs were taken using glycerol-treated aggregates after MacEwan (1949). The method of thermal analysis will be described in a later paper.

* Calculating from the K_2O content of the clay (0·60%), assuming that illite contains 5% K_2O as a maximum (Alexander, Hendricks, and Nelson, 1939), this sample contained 12% illite.

† The substance giving a peak at about 345° C. was assumed to be free iron oxide similar to that recorded by Mackenzie (1949).

n.d. Not determined.

The krasnozem soils support the results obtained elsewhere, showing no montmorillonite or illite and being composed entirely of kaolinite together with the oxides of iron and aluminium.

These results show the relationship between the soils derived from basalt and the climate and topography. Thus the condition of high pH and base saturation found in chernozems produces a clay predominantly of the montmorillonite-beidellite group. Such conditions will be found in the drier climatic areas over most, if not all, of the catena, but in progressively wetter areas they will be found only in the progressively lower positions.

The absence of such pronounced base concentration in the chocolate soils, due either to their higher topographic situation and/or the higher rainfall, appears to be associated with a partial or perhaps more rapid breakdown of the montmorillonite-beidellite lattice, especially in the eluvial horizons, and the formation of kaolinite and illite.[1] In the krasnozems, however, the soil condition is too acid and the degree of base saturation too low to maintain a montmorillonite-beidellite type clay. With the collapse of the montmorillonite lattice, the excess of iron is released and remains as oxides and hydroxides, since the kaolinite lattice is unable to accommodate the larger iron ion.

Discussion

The pattern of soil development shown by the catenas described above is similar to those originally described by Milne (1936) in East Africa. It can be interpreted as due to differences in the intensity of weathering, the soils formed being in dynamic equilibrium with their environment and the base status of each soil being the result of the balance between loss by leaching and input from rock weathering and ground water. The soils formed on different parts of the same catena are in different positions relative to this last factor.

In the simplest case, four sites, A, B, C, and D, on the catena as shown in Fig. 9 may be considered. The leaching of the soil forming on site A is relatively simple. This soil is losing bases to the water which enters after rain and drains through the soil to the ground water. Since the leaching water in this case will at first contain only the very low concentration of bases present in the rain, the exchange of soil bases for the hydrogen of the leaching water will be a maximum.

The soils in position B, however, will receive water that has run off from the top of the hill in addition to rain-water. This run-off water will carry a higher concentration of bases than the rain-water. In addition to leaching vertically by water entering from the surface, the lower horizons of profiles at site B may also be receiving ground water percolating laterally that has entered and drained through the soil on the top of the hill. The water percolating through the profile at site B will consequently be richer in bases than that leaving site A.

Similar conditions will obtain at sites lower down the slope (at C and D), except that the surface and ground water will become progressively

[1] The presence of illite in soils derived from basalt is surprising but is presented without further comment at this stage.

richer in bases. The waters percolating through the profile at the lower parts of the catena will in consequence be less able to remove bases from the soil. If the concentration of bases and the pH of the percolating water rise sufficiently, the position will be reached where the least soluble base will be precipitated during dry periods. This is the condition under which calcium carbonate would be deposited.

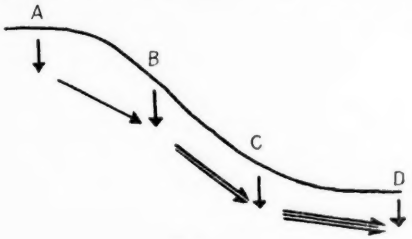

FIG. 9.

In the ideal catena on basalt in a dry climate there will be a progressive increase in the base content of the lower members of the catena, inducing the formation of the progressively less leached soils: chocolate—prairie—chernozem—sierozem.

As the effective rainfall increases, the amount of water percolating through the soil will increase. Two results follow from this. In the first case the top member of the catena is now subject to increased leaching, both by virtue of the increased throughput of water and by the increased acidity of this water due to the greater amount of organic matter produced. If it is assumed that the base input on to the exchange complex remains the same, namely, that from rock weathering, then the base-status of the resulting soil must be lowered, and the top member of the catena changes in the first instance from chocolate to transitional krasnozem, and with further increase in rainfall to krasnozem.

As a result of the increased precipitation, the concentration of bases in the percolating waters is lowered, as is that of soluble salts, so that the concentrations necessary for precipitation of gypsum and calcium carbonate obtain over progressively smaller proportions of the catena until sierozem and chernozem soils are replaced on the lower positions by the chocolate soils, with prairie and meadow soils occupying the lowest sites.

With greater leaching, the concentration of bases in the leaching waters becomes so low that the chocolate soils are not developed, and the upper parts of the catena are occupied by krasnozems, with prairie and meadow soils on the lowest sites. With maximum leaching krasnozems occupy literally all of the catena.

The above climatically induced changes in the catenas indicate how topography becomes progressively less important as a soil-forming factor as the intensity of leaching is increased.

The relationship between the top members of these catenas requires further discussion. In spite of certain similarities in profile features (such as pH of topsoil, colour, and absence of secondary carbonates) of

the top catena members encountered at the climatic extremes, namely, reddish chocolate and krasnozem, there are sufficient differences to warrant their separation as distinct soil groups. The outstanding differences are as follows:

	Reddish chocolate	*Krasnozem*
Visible porosity	Closed	Porous
Handling consistency	Compact to tenacious	Friable
Structure	Crumb to small cloddy in top soil, becoming almost massive in the subsoil	Fine crumb structure throughout the profile

This difference appears to be a reflection of the marked differences in the constitution of the clays shown above (Table 4), the clay in the reddish chocolate being largely montmorillonitic with only a trace of free sesquioxides, whilst the clay of the krasnozems contains no montmorillonite, but is kaolinite together with oxides of iron and aluminium, the latter constituting about half of the clay fraction. The higher organic matter content of the krasnozems would augment the difference. The effect of this on the vegetation is mentioned later.

The significance of the catenas described above is that in the drier areas the soils change, proceeding from the top to the bottom of the catena, from the more leached to the less leached forms. Both the Cooma and Mooki catenas, for instance, show the sequence to be from reddish chocolate to normal chocolate to chernozem and in one case to sierozem, whilst the pH figures show a progressive increase. This is in contradistinction to the more generally accepted impression that the bottom catena members are the locally more humid, and therefore more leached. The explanation offered here is that not only the transport of water but also the transport of bases is affected by the topography.

The exact nature of the change in base status of the soils and the consequent catenary sequences of progressively less leached or more leached soils will depend not only on the amount of percolating water as such, but also on changes in the ratio or balance of bases to water. These changes may vary independently. In the case of basalt in a somewhat dry climate, the ratio of base to water increases from top to bottom of the catena, producing a corresponding sequence of progressively less leached soils, in which there is a maximum difference between top and bottom members. In moister climates the ratio of bases to water still increases down the catena but to a lesser extent, again resulting in a sequence of soils progressively less leached from top to bottom, but with a narrower range of difference. Proceeding to the most humid climate there is no appreciable increase in the base to water ratio from top to bottom of the catena, and consequently the soils show no significant change in the degree of base saturation, and the same soil group, the krasnozems, occupies all positions on the catena.

The vegetation of the chocolate and related soils

The chocolate soil areas of New South Wales demonstrate the preciseness of the relationships which may exist between soils, vegetation, and climate. The vegetation of the reddish chocolate and normal

chocolate soils is either grassland or savannah woodland, whilst that of the grey chocolate soils is always savannah woodland. Nowhere have typical chocolate soils been found associated with forest.

In their colder southern limits in the Monaro region, the reddish chocolate soils support a grassland dominated by corkscrew grasses (*Stipa scabra* Lindl., *S. variabilis* Hughes, and *S. bigeniculata* Hughes), whereas in the warmer northern areas in the Namoi region a savannah woodland of white box (*Eucalyptus albens* Miq.) and Blakely's red gum (*E. Blakelyi* Maiden) is characteristic. The absence of savannah woodland on the reddish chocolate soil of the Monaro is probably due to the lower temperatures of this region, which exclude *E. albens* and *E. Blakelyi* from otherwise suitable environments. Among the savannah woodland species of the Monaro region that are able to tolerate lower temperatures than can *E. albens* and *E. Blakelyi* none is sufficiently adapted to the combination of lower rainfall and poorly aerated subsoil conditions of the reddish chocolate soils, with the result that grassland is the climax vegetation.

A comparable situation exists with the normal chocolate soils, which in the Namoi region and New England always support a savannah woodland of *E. albens* and *E. Blakelyi*, or on the Monaro either grassland with *S. scabra*, *S. variabilis*, and *S. bigeniculata*, or a savannah woodland with white sally (*Eucalyptus pauciflora* Sieb. ex Spreng.), manna gum (*E. rubida* Deane and Maiden), black sally (*E. stellulata* Sieb. ex D.C.), ribbon gum (*E. viminalis* Labill.), and blackwood (*Acacia melanoxylon* R.Br.). The grasslands occur on the normal chocolate soils of the drier areas on the Monaro where low temperatures exclude the more mesothermal savannah woodland species, such as *E. albens* and *E. Blakelyi*, and inadequate soil moisture the more cold-resistant species *E. pauciflora*, *E. rubida*, &c. With increased precipitation the moisture relations become satisfactory for the latter species and grassland is replaced by savannah woodland as the climax vegetation.

The vegetation of the grey chocolate soils is savannah woodland. Because of the lower temperatures in which the grey chocolate soils occur, the more mesothermal tree species are excluded, and the dominant species are *E. pauciflora*, *E. rubida*, *E. stellulata*, *E. viminalis*, and *A. melanoxylon*.

In a given area of basalt on the Monaro, for example, where the precipitation gradient increases sufficiently without a decrease in temperature, there is an abrupt transition from normal or grey chocolate soils with savannah woodland to acid red loams with wet sclerophyll forest dominated by cut tail (*E. fastigata* Deane and Maiden), spotted mountain gum (*E. goniocalyx* F. Muell. ex Miq.), broadleaved messmate (*E. obliqua* L'Herit.), mountain gum (*E. Dalrympleana* Maiden), and ribbon gum (*E. viminalis* Labill.). Under these conditions the soil-vegetation-climate relationships are most precise.

The characteristic subsoil constitution is considered partly responsible for the dominance of grassland or savannah woodland on chocolate soils in climates favourable for forest vegetation. In contrast to grasses, which are relatively surface rooting, and to savannah woodland trees,

whose roots derive a large part of their moisture needs by spreading laterally near the surface rather than vertically, most closely packed trees of Australian forests can satisfy their moisture requirements only if the roots penetrate also to the deep subsoil and to greater depths. In soils from most coarse to medium textured parent materials, this deeper root penetration is not prevented by any physical property of the soil itself. In the case of the chocolate soils formed on basalt, however, the subsoil is typically closed and compact and therefore so imperfectly aerated that tree root development in or beyond the subsoil is inhibited. Accordingly, even though the subsoil moisture content of chocolate soils in moister localities may be quite adequate for forest vegetation, this source of moisture is rendered unavailable to tree roots by poor subsoil aeration. In climates which may be suitable for forest vegetation, therefore, only savannah woodland or grassland is able to develop. It is significant that exotic tree species such as *Salix babylonica* L. (weeping willow) and *Populus alba* L. (white poplar), which are noted for their tolerance of poorly aerated soils, grow quite successfully on those chocolate soils of the Monaro region from which trees are naturally absent.

Summary

A study has been made of the morphological and certain analytical characteristics of a group of soils developed on basalt. These soils appear to be sufficiently distinct from related soils to merit their separation as a new great soil group—the chocolate soils.

This group has been divided into three sub-groups, the reddish chocolate, normal chocolate, and grey chocolate soils.

An interpretation of their relationships among themselves and to other groups is given in terms of intensity of weathering as affected by the interaction of topography and climate.

The distinctive vegetation association of the sub-groups is described.

Acknowledgements

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THE INFLUENCE OF NEUTRAL SALTS ON THE SOLUBILITY OF SOIL PHOSPHATE

WITH SPECIAL REFERENCE TO THE EFFECT OF THE NITRATES OF SODIUM AND CALCIUM

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IT is known that salts of different cations affect the solubility of soil phosphate in different ways. The results of experiments with phosphate compounds of low solubility have suggested that solubility is increased by some cations and reduced by others. This problem is important in view of the high rate of fixation of phosphate applied to cultivated soils and consequent low recovery in crops. It is an inseparable part of this more general problem of phosphate retention that all salts, applied as fertilizers, influence the availability of soil phosphate. Special interest is directed by the authors to the sodium ion, which has often been said to act as a mobilizer of soil phosphate.

Wild (1950), in a recent review, has referred to the results of phosphate extraction with solutions of different salts, and concluded that there is as yet insufficient accurate information to explain the apparently contradictory findings of different investigators. The present authors have investigated the influence of series of salts on the solubility of phosphate in different types of Dutch soils, with special regard to the comparative effects of sodium nitrate and calcium nitrate.

Experimental

Preliminary investigation showed that the results obtained in percolation experiments are erratic and, for that reason, unsatisfactory. This was also the experience of McGeorge and Breazeale (1931), who referred to difficulties caused by slow leaching, coloured filtrates, channelling, and puddling. The present authors found, in successive leachates collected at intervals from one and the same soil, some evidence of enhanced solution of phosphate (Fig. 1), suggesting that phosphate 'solubility' depends on the rate of percolation.

Mattson and co-workers (1950) established that in extraction experiments the solubility of soil phosphate depends on the soil : water ratio. It is not surprising, therefore, that the results of percolation experiments are inconsistent. The present authors adopted a technique involving a single extraction with each salt solution. This method is simpler and quicker than percolation, and the results obtained by it are much more consistent than those of percolation trials. Disregarding variation due to differences of technique, the results from the two methods are similar (Fig. 2).

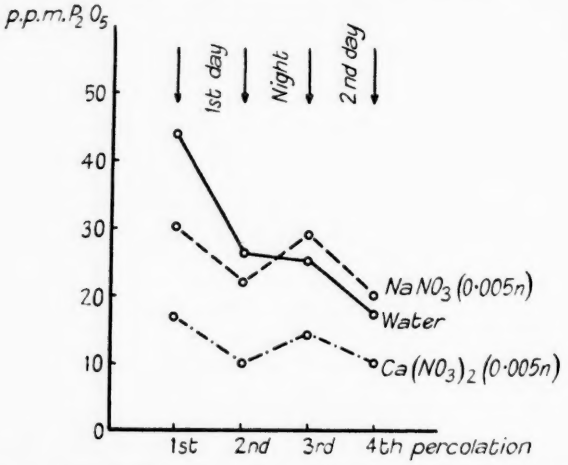

FIG. 1. Percolation experiment with soil. In successive leachings declining amounts of soil phosphate are extracted with different reagents, but on interrupting the experiment (standing at night) a liberation of phosphate occurs.

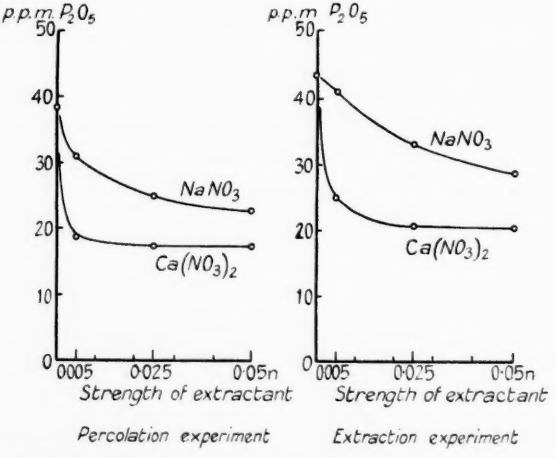

FIG. 2. Percolation and extraction experiments with soil produce similar results, but much more consistent with the extraction method than with the percolation method.

Procedure. Ten grammes of air-dry soil were thoroughly mixed with 50 c.c. of distilled water or salt solution. After standing for 12 hours the mixtures were shaken for 2 hours and then filtered. The extracts were refiltered through the mat of soil until clear. Any organic matter present

in the filtrate was oxidized with permanganate in an acid medium, and the phosphate was determined colorimetrically by the molybdenum-blue method. By using the Lumetron No. 400A photo-electric colorimeter, error in measurement of the results was limited to about 0·5 part per million of P_2O_5.

Influence of salts. Although many experimenters have studied the influence of salts on phosphate solubility, search of the literature has not revealed any records of systematic investigation of the influence of complete salt series on the solubility of soil phosphate.

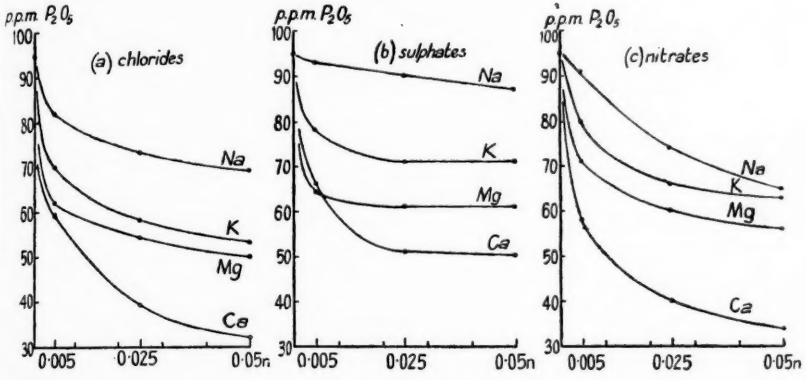

FIG. 3. Effects of different salts on the solubility of the soil phosphate of a phosphate-rich sea clay ('terp' soil from Baflo). All neutral salts decrease the solubility of soil phosphate; sulphates only to a slight extent. For different cations the depression is in the order of the lyotropic series: Na < K < Mg < Ca.

In the experiments with different kinds of soil, now described, solubility of phosphate in solutions of neutral salts was invariably less than in pure water. Solubility decreased with increasing concentration of the solutions.

The graphs in Fig. 3 illustrate the effects of different salts on the solubility of the phosphate of a phosphate-rich sea clay soil (so-called 'terp' soil[1]), from Baflo in Groningen Province. The letters *a*, *b*, and *c* refer respectively to the chlorides, sulphates, and nitrates of sodium, potassium, magnesium, and calcium. The solutions were of equivalent concentrations, respectively 0·005 N, 0·025 N, and 0·05 N. In the case of calcium sulphate, calculated quantities of the solid substance were added, because the highest concentration of solutions was above the solubility of this salt (0·028 N).

All these salts followed the lyotropic series in their influence on phosphate solubility. Depression of solubility was in the order:

sodium < potassium < magnesium < calcium.

[1] The nomenclature of Edelman (1950) has been adopted as far as possible for the description of the various soil types.

There is fairly close resemblance between the solubility curves for nitrates and chlorides. In the case of sulphates, however, the reducing effect on solubility is less marked and the curves assume a horizontal trend with the higher concentrations. This exceptional behaviour of sulphates will be referred to later.

The graphs in Fig. 4 refer to a light river loam from Breedenbroek (Achterhoek district), a soil with a lower phosphate content than the Baflo sea clay. However, they display exactly the same features noted in Fig. 3.

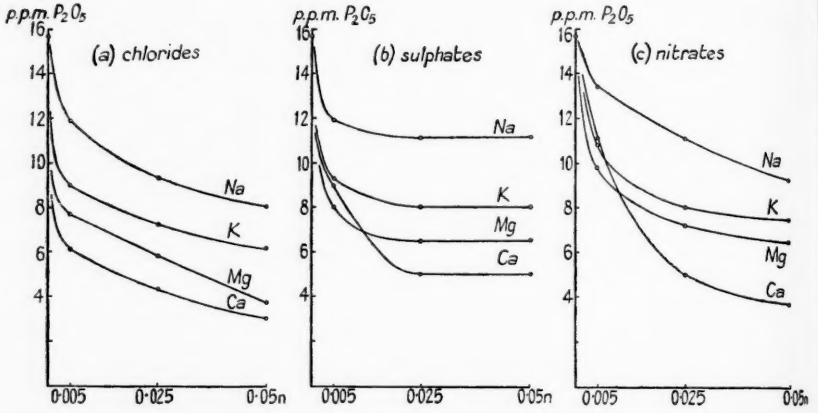

FIG. 4. Effects of different salts on the solubility of the soil phosphate of a river loam soil (from Breedenbroek). The curves are similar to those of Fig. 3.

Sodium nitrate and calcium nitrate. In order to study further the influence of the sodium ion on the phosphate economy of different soil types sodium nitrate and calcium nitrate were specifically compared (already illustrated in Figs. 2, 3, and 4). Calcium was selected for this comparison because of its major practical importance and because it is the predominating cation in most Dutch soils. Ammonium salts are less suitable for the purpose as they take part in a variety of reactions in the soil and, consequently, their effect in the field may well differ considerably from that in the laboratory. In general, calcium nitrate is the end product of the conversion of ammonium salts in the soil (via interchange at the complex), but the process is accompanied by a complicating acidifying effect. An illustration of the behaviour of ammonium salts in laboratory tests is provided by Fig. 5, which includes solubility curves for ammonium nitrate and ammonium sulphate as well as for the nitrates of sodium and calcium. It will be observed that the ammonium curves occupy approximately the position held by the potassium curves in Figs. 3 and 4.

To study more closely the behaviour of different soil types and to obtain at the same time an impression of the way in which nitrate dressings influence the phosphate availability, 22 representative samples of

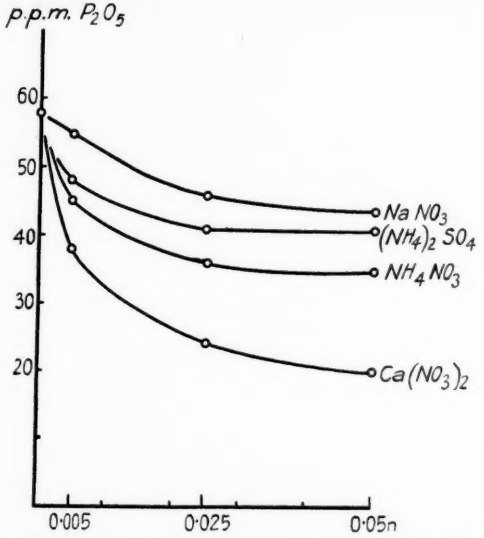

FIG. 5. Extraction experiment with a peaty clay soil (from Woerden). Comparison of the effect of ammonium nitrate and ammonium sulphate on the solubility of soil phosphate with that of sodium and calcium nitrates.

Dutch soils were investigated on their reaction to the nitrates of sodium and calcium. These soils can be grouped in the main as sandy, loamy, river clay and marine clay. The phosphate solubility was studied in pure water and with salt concentrations of 0·005, 0·025, and 0·05 N.

0·025 N corresponds to the nitrate (NO_3) concentration in the soil solution resulting from the even distribution of 105 kg. of nitrogen per ha. (93·7 lb. per acre) over a soil layer of depth 20 cm. (7·9 in.) and containing 10 per cent. of moisture. In actual practice, considerably higher local concentrations will be found in the upper soil layers immediately after the dressing and especially if accompanied by the application of potassic fertilizers.

Table 1 reflects how the nitrates with the highest concentration influenced the phosphate solubility in the principal soil types.

TABLE 1

Range of Solubility of Soil Phosphate of Different Dutch Soil Types in 0·05 N Solutions of Sodium Nitrate and Calcium Nitrate expressed as a Percentage of the Phosphate Solubility in Pure Water

	$NaNO_3$		$Ca(NO_3)_2$	
	Range	*Average*	*Range*	*Average*
Sandy soils . .	32–66	53	9–50	29
Loamy soils . .	53–75	68	21–50	33
River-clay soils . .	57–89	72	43–44	44
Sea-clay soils . .	50–86	67	13–50	35

Setting aside differences in degree of phosphate level and solubility, all tested types of Dutch soils reacted to the nitrates in the same way. Sandy and loamy soils are on the whole somewhat more sensitive than river clays and sea clays. The humus content of humic sandy soils (old arable land) tends to reduce the effect of the salts; there was less fixation of phosphate in soils with the higher humus contents—peaty soils probably occupy a special position. Among clay types, very young soils (recent young marsh silt) behave somewhat differently, seeming to be more sensitive to added salts. No correlation was found with soil pH. It could be said generally that the soil phosphate was appreciably more soluble in solutions of sodium nitrate than in corresponding solutions of calcium nitrate. For 0·025 N and 0·05 N concentrations, respectively, solubility in sodium nitrate is on average 80 per cent. and 90 per cent. higher than in calcium nitrate. It is difficult to estimate as yet the extent to which the described phenomenon, namely, the influence of other fertilizer salts on the phosphate availability, occurs in field practice, but it can hardly be doubted that it does occur to a measurable degree. It may, therefore, be important for the phosphate supply of the crops which cations are added beside potassium with the other fertilizer salts.

Organic phosphate. No special attempt has been made in the experiments described to determine the presence of phosphate in organic compounds. So far as soils poor in organic matter were concerned, organic phosphate cannot have had any marked influence. The extracts from these soils were at most slightly tinged. On the other hand, in the case of some humic soils the extract with sodium nitrate was darker in colour than that with calcium nitrate, and the question arose whether some organic phosphate, e.g. a complex phosphohumate, had been extracted. As coloured extracts interfere with the colorimetric determination of phosphate, organic matter was destroyed by oxidation with permanganate. This process might, however, increase determinable phosphate. That this was not the case was demonstrated by clarifying the extract with activated charcoal instead of oxidizing it with permanganate. Following this treatment, which entirely removed any humates, the total quantity of phosphate could be determined in the solution, as illustrated by the following example:

Treatment of the soil extract	*p.p.m.* P_2O_5
(1) Organic matter oxidized with $KMnO_4$	40·3
(2) The same, and treated with activated charcoal	45·7
(3) Extract only, treated with activated charcoal	45·7

Reversibility of effect. An attempt was made in some instances to determine whether dilution causes an *increase* in solubility of the phosphate, as stated by Mattson and co-workers (1950).

Ten grammes of soil were shaken in the ordinary way with 50 c.c. of the solution; after settling 25 c.c. were pipetted and centrifuged; phosphate was determined in the supernatant liquid as in the preceding investigation. The separated soil along with 25 c.c. of distilled water was added to the remaining soil suspension. The mixture was stood overnight and then shaken for 2 hours, after which 25 c.c. of solution

were again pipetted. The process was repeated three times in order to ascertain the effect of dilution on phosphate solubility.

The results for two types of soil are shown in Fig. 6. With calcium nitrate there was no evidence of reversal of effect. Increasing dilution was accompanied by a decline in phosphate solubility, which commenced after the second dilution and was approximately proportional to the

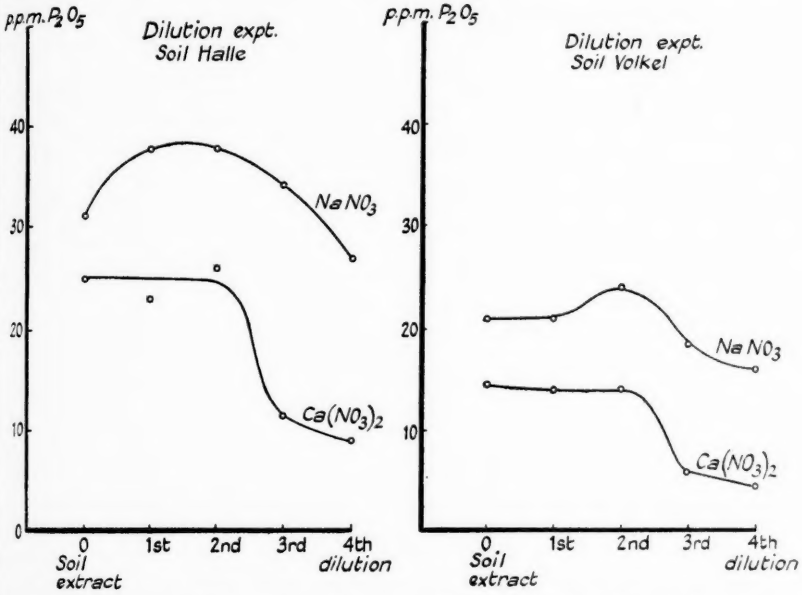

FIG. 6. Experiment to investigate the reversibility of the effect of neutral salts on the solubility of soil phosphates. With $NaNO_3$ a measurable resolution of phosphate could be established; with $Ca(NO_3)_2$ increasing dilution only resulted in declining phosphate solubility.

dilution. With sodium nitrate there was a measurable increase in solubility of the soil phosphate, and release of phosphate was continued for a longer period than with the calcium salt.

Discussion

It is generally assumed that iron, aluminium, and calcium are largely responsible for the fixation of phosphate in the soil. Iron is most active in very acid soils, and calcium in slightly acid, neutral, and calcareous soils. The results of laboratory experiments, such as those carried out by Teakle (1928) and Gaarder (1930), suggest that aluminium is most active in precipitating phosphate in slightly acid soils. However, under such conditions, silicic acid and humic acid may inactivate aluminium, while calcium remains active. Even in slightly acid soils, therefore, more significance should be attached to the influence of calcium on phosphate

fixation. An important observation was made by Barbier and Chabannes (1949) to the effect that phosphate fixation by calcium (adsorbed to clay in exchangeable form) is a rapid reaction, whereas fixation by iron and aluminium (forming part of the complex) is a much slower process. Ravikovitch (1934) gives an interesting example of phosphate fixation by adsorbed calcium.

Soil phosphates. In the soil, calcium phosphate commonly occurs as part of compounds with the general formula $3Ca_3(PO_4)_2.CaX_2$, in which X may be F, or OH, or $\frac{1}{2}CO_3$. The best known of these compounds is hydroxy-apatite ($3Ca_3(PO_4)_2.Ca(OH)_2$) which, according to Lohse and Ruhnke (1933), would be the most stable form of calcium phosphate, even in slightly acid solution. Its presence in the soil is almost certain, because it is a product of the hydrolysis of dicalcium phosphate by water (Warington, 1873; Rathje, 1939). On the other hand, the work of MacIntire and his associates suggests that dicalcium phosphate is not rapidly converted and may persist as such even in the presence of calcium carbonate. As to the existence of tricalcium phosphate as such considerable doubt has been cast by several investigators, e.g. Shear and Kramer (1928) and Rathje (1939).

Further investigation is required to determine the effect of salt additions on these various forms and combinations of calcium phosphate.

Influence of soil. Treatment with salts of sodium, potassium, or ammonium often increases the solubility of pure phosphates of low solubility. On the other hand, soil phosphate becomes less soluble when treated with calcium salts, as well as with salts of the univalent ions mentioned. Greaves (1910) has pointed out that the results of experiments with pure phosphates may differ from those with soil phosphates because of interference due to reaction between salt solution and soil. The present authors have demonstrated such interaction in a simple manner. Treatment with salts of sodium, potassium, or ammonium increased the solubility of dicalcium phosphate, while calcium salts caused a decrease in solubility due to the common ion effect (Table 2). When, however,

TABLE 2

Solubility of $CaHPO_4, 2H_2O$ *in Different Salt Solutions in mgm.* P_2O_5 *per Litre*

Substance	*0·0*	*0·005 N*	*0·025 N*	*0·05 N*
Water . .	62	..	..	..
$NaNO_3$ . .	..	70	86	100
Na_2SO_4 . .	..	75	102	128
KNO_3 . .	..	70	87	100
NH_4NO_3 . .	..	70	96	117
$Ca(NO_3)_2$ . .	..	38	25	21

dicalcium phosphate was treated with an extract made by shaking soil with a solution of sodium nitrate, solubility of the phosphate was lowered, despite the fact that the soil extract itself already contained some phosphate (Table 3). This was also true of sodium sulphate and was especially striking with potassium nitrate, which alone increased the solubility of

dicalcium phosphate from 62 to 97 p.p.m., and after interaction with soil decreased it to 44 p.p.m.

TABLE 3

Phosphate Content in mgm. P_2O_5 *per Litre in Extracts of* (*a*) $CaHPO_4$: *Salt Solutions,* (*b*) *Soil*: *Salt Solutions, and* (*c*) $CaHPO_4$:*Soil Extracts*

	Water	$NaNO_3$ *0·05 N*	Na_2SO_4 *0·05 N*	KNO_3 *0·05 N*
(*a*) Extract $CaHPO_4$	62	97	123	97
(b_1) Extract Halle soil (No. 4) . . .	..	6	7	..
(c_1) Extract $CaHPO_4$ with extract b_1 . .	..	64	82	..
(b_2) Extract Baflo soil (No. 22) . . .	..	16	18	13
(c_2) Extract $CaHPO_4$ with extract b_2 . .	..	67	84	44

In fact, the interaction described is associated with replacement of calcium at the adsorptive complex by other cations. An excess of calcium (as common ion) has a depressing effect on the solubility of calcium phosphates. McGeorge and Breazeale (1931) have described the influence of calcium in the following words: 'Salts of the monovalent bases reduce phosphate solubility in calcareous soils because they increase the solubility of calcium.' Mattson and co-workers (1950) have also referred to this effect of calcium. Teakle (1928) demonstrated the effect in a different way. He shook soil with a solution of ammonium oxalate. Calcium was rendered inactive as calcium oxalate, and there followed a marked increase in the solubility of phosphate. Teakle has even suggested that reduction of the solubility of phosphate by ferric chloride is not necessarily due to the iron ion itself, but may originate from hydrolysis of the ferric chloride, with formation of hydrochloric acid and increased solubility of calcium. Regarded in the light of phenomena of exchange, it is clear why the influence of the cations follows the lyotropic series (Figs. 3 and 4), as the calcium-replacing capacity increases in the order: $Na < K < Mg < Ca\ (= 1)$.

Sulphates. Sulphates occupy a special position in extraction experiments. The explanation of this exceptional behaviour probably lies in the formation of calcium sulphate, a salt of low solubility which in solution soon reaches saturation. An excess of calcium sulphate cannot further increase calcium concentration in the soil and, therefore, remains without influence on the solubility of soil phosphate. For the explanation of the different behaviour of the sulphates of sodium, potassium, and magnesium (see Figs. 3 and 4) it should further be considered that these cations exchange calcium to a varying extent. Accordingly, on shaking solutions of the said sulphates with soil, they will reach saturation at different ratios of calcium:sulphate, being determined by the solubility product of calcium sulphate.[1] This explains why the curves in Figs. 3 and 4 reach a horizontal trend at different levels.

[1] A saturated solution of $CaSO_4$ corresponds to 0·014 molarity (= 0·028 N). From the solubility product ($6{\cdot}1 \times 10^{-5}$) the Ca- and SO_4-concentrations can be computed to be $7{\cdot}8 \times 10^{-3}$, corresponding to about 0·016 N. This apparent discrepancy, probably due to the presence of undissociated $CaSO_4$, complicates explanation of the sulphate effect.

From a point of view of fertilizer economy sulphates are on account of their exceptional behaviour among the best salts to accompany phosphates used as fertilizers.

Application to practice. It may be asked how far what has been learned about the effect of neutral salts may be applied to the phosphate economy in the field. Phosphate fixation is a serious practical problem which, in the opinion of the present authors, is affected by the nature and action of other salts applied as fertilizers along with phosphates. Eriksson (1942), for example, showed this to be the case with potash fertilizers. There is urgent need for further investigation of means of reducing the extent of fixation and of increasing the efficiency of phosphatic fertilizers.

Without wishing to pronounce prematurely on the practical significance of the neutral-salt effect, attention may justifiably be directed to the following point: The effect of applied fertilizer salts on the solubility of the phosphates of soil and fertilizers will no doubt be greatest immediately after application. Thereafter, absorption of salts by the growing crop and leaching of salts in the autumn are likely to be accompanied by a decline in the salt effect, resulting in increased solubility of phosphate.

The results of laboratory trials have shown that dilution following the application of sodium nitrate produced a measurable re-solution of phosphate, but no such effect was observed with calcium nitrate. This salt, on dilution, caused a more rapid fall in available phosphate (Fig. 6). Of all cations, sodium is most effective in retarding retention of phosphate, and in maintaining its availability.

Summary and Conclusions

1. In laboratory trials with different types of Dutch soils, all neutral salts decreased the solubility of the soil phosphate. The effect was more pronounced with higher salt concentrations.

2. In the case of salts with the same anion, the depressing effect on solubility of soil phosphate increased in the order of the lyotropic series: $Na < K < Mg < Ca$.

3. Conflicting results obtained when neutral salts are added to soil phosphates on the one hand and to pure phosphate compounds on the other may be explained by interaction between salt solution and soil. Replacement of calcium by other cations at the adsorptive complex is the principal operating factor. This also affords explanation of the effect mentioned in 2.

4. Sulphates occupy a peculiar position. At the higher concentrations their adverse effect on phosphate solubility was less marked than that of chlorides and nitrates, probably because of the formation of insoluble calcium sulphate.

5. The solubility of the phosphate of twenty-two different Dutch soils in solutions of calcium nitrate and sodium nitrate was investigated. At such levels of nitrate concentration as may be expected in the soil after the application of nitrate fertilizers, solubility of the phosphate was on average 80 to 90 per cent. higher with sodium nitrate than with calcium nitrate. On sandy and loamy soils the effect of neutral salts on the solubility of soil phosphate was more marked than on river clays and

sea clay. The higher humus content of humic sandy soils tends apparently to reduce the salt effect. No clear relation between salt effect and soil pH was observed.

6. In laboratory experiments a measurable increase in solubility of the soil phosphate followed dilution in the case of sodium nitrate, but with calcium nitrate no significant increase was noted. In leaching experiments, sodium salts tend to maintain a larger and more prolonged subsequent release of soil phosphate than do calcium salts.

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A FIELD METHOD OF MEASURING THE SHEAR STRENGTH OF SOILS

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Summary

Soil shear strength is a property likely to affect the performance of cultivation implements. Existing methods of measuring this property have been found unsuitable for cultivated top soils, principally because of the difficulty of obtaining an undisturbed sample. A field method of determining shear strength is described in which a cylinder of soil is sheared in torsion and a moment/angle-of-twist (proportional to strain) curve obtained. From this the shear-stress/angle-of-twist can be obtained mathematically. Where only the maximum shear strength is required a simplified method is given. A number of results using the apparatus on widely differing soil types is given, together with a comparison of some of these with results from the standard shear box.

Introduction

THE effect produced on a soil by cultivating implements, and the forces acting on those implements, must both depend upon the mechanical properties of that soil. These may be considered in two ways: those of a bulk sample containing innumerable clods and small particles, and those of the individual clods. It seems likely that the properties of the former have the greater effect on implement draught and that most of the energy absorbed in tillage is used in soil-to-implement friction, the compression of soil, and the lifting and shearing of soil. It is with the measurement of the last of these that this work is concerned. Shear strength is defined as the force required to cause sliding between two soil surfaces of unit area. Civil engineers are normally concerned with the maximum static value of this just before sliding begins; but it seems likely that, in studying implements, the dynamic value after sliding has started will also be required.

Coulomb, in 1773, suggested that shear strength could be divided into two parts, given by the following equation:

$$s = c + \rho \tan \phi,$$

where, in modern nomenclature,

s = shear strength,
c = apparent cohesion,
ρ = pressure normal to shear plane,
and ϕ = angle of shearing resistance.

The cohesive component is independent of the normal pressure, while the frictional component is a function of the normal pressure. The apparent cohesion and angle of shearing resistance are empirical constants whose values hold good only under a given set of soil and testing conditions. They are, therefore, only of value if obtained under similar conditions to those prevailing where they are to be applied.

Disadvantages of Existing Methods

It is considered impossible to take a truly undisturbed sample of cultivated soils and hence, though it may be possible to use more sensitive apparatus in the laboratory, such as the shear box, triaxial and annular testers, the advantage is outweighed by the impossibility of working with a representative sample. This difficulty may not be as important in the sub-grades commonly handled by civil engineers, but for the present purposes an *in situ* method was required.

An instrument which has frequently been used on silts and clays at great depth, but which can be used for surface soils, is the vane (Smith, 1945; Carlson, 1948; and Evans and Sherratt, 1948). This instrument is used in the field and therefore overcomes sampling difficulties, but although the value of the shear strength under natural unloaded conditions can be found and calibrated directly against bearing capacity, the two parameters c and ϕ cannot be separated. Other soil tests such as the California bearing ratio determination and the Proctor needle test, though measuring properties that are undoubtedly related to shear strength, do not give direct values to this quantity.

As none of the existing methods was considered satisfactory for agricultural soils, it was decided to attempt to develop a new technique that would work *in situ* and give the shear strength at various normal pressures. After a number of preliminary trials employing other principles had been tried, the torsional shear box described below was developed.

The Torsional Shear Box

The apparatus (Fig. 1) consists of a cylindrical torsion box (A) 5 in. in diameter and 2 in. deep with a removable lid (B), a torque-meter similar to that used with the conventional vane (C), a removable wire pointer 36 in. long (D), and a series of slotted lead weights (E). On the inside of the walls of the torsion box there are six equally spaced small fins 2 in. long, $\frac{3}{16}$-in. wide, and $\frac{1}{32}$ in. thick which prevent the soil from slipping relative to the box.

In use, the torsion box is forced into the soil in the field to its full depth, the appropriate number of weights added, and the surrounding soil removed. The soil is cleared down to a depth of about $\frac{1}{8}$ in. below the bottom of the box to prevent its edges from carrying any of the normal load applied, but not far enough to lessen, appreciably, the strength in compression of the short cylinder of soil exposed. Fig. 3 is an exaggerated diagram of this cylinder. The long pointer (D) is inserted to its mid-point, and scales (G) placed below it at each end to read its deflexion. It is best to read both ends at the same time and take the mean, since this reduces errors due to a bent pointer or to the sample not twisting about the centre. A twist is applied manually to the handles (F) of the torque-meter at as near a constant speed as possible. The usual time taken for the twisting couple to reach 100 lb. in. is half a minute. The deflexions of the ends of the pointer are recorded for as many values of the torque as possible. If the maximum shear strength only is required,

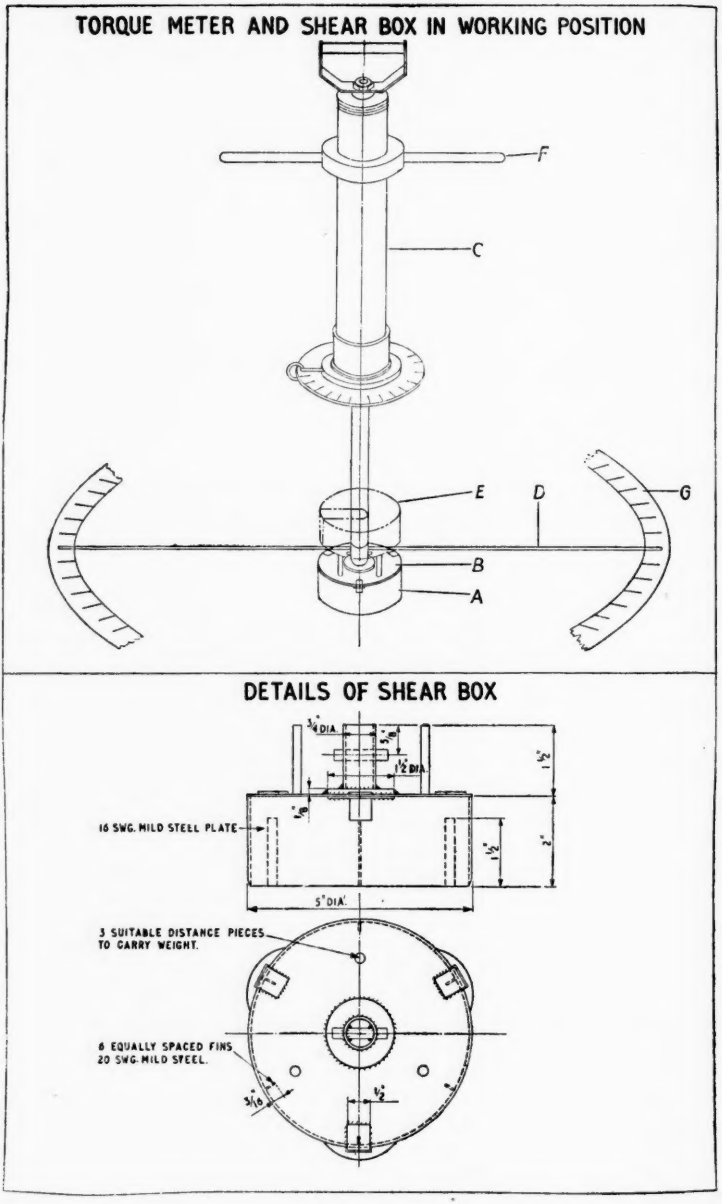
TORQUE METER AND SHEAR BOX IN WORKING POSITION
F
C
E
D
G
B
A
DETAILS OF SHEAR BOX
¾" DIA
⅝"
½" DIA
1½"
⅜"
16 SWG. MILD STEEL PLATE
1½"
2"
5" DIA.
3 SUITABLE DISTANCE PIECES TO CARRY WEIGHT.
6 EQUALLY SPACED FINS 20 SWG. MILD STEEL.
3/16
½"

FIG. 1.

the test is stopped as soon as the torque passes its maximum: if the dynamic shear strength is required as well, the steady value to which the torque drops after the sample has yielded must be recorded. Some difficulty has been experienced in practice in finding this value with the present simple torque-meter, and it may be necessary to mount the apparatus on a tripod and to provide the torque through gearing where large angles of twist of the order of whole revolutions are needed.

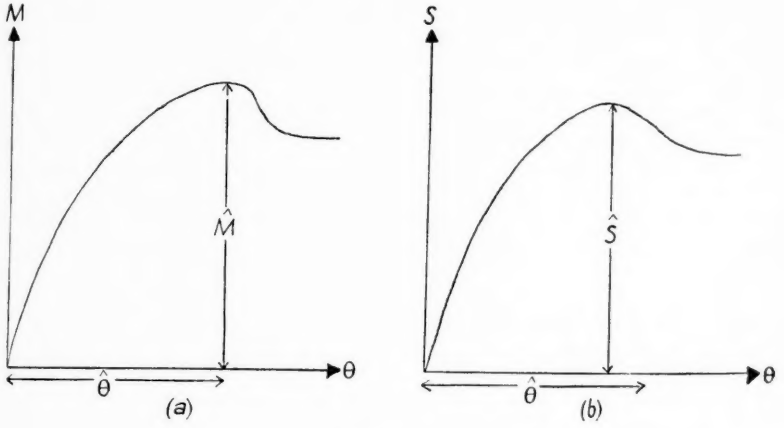

FIG. 2.

The moment-twist curve, of which Fig. 2(*a*) shows the usual form, is then plotted, and the shear strength for the appropriate angle of twist calculated from the equation (a):

$$s = \frac{3}{2\pi r^3}\left(M + \frac{\theta}{3}\frac{dM}{d\theta}\right), \qquad \text{(a)}$$

where,

s = shear strength in lb./sq. in.,
r = radius of torsion box in inches,
M = applied twisting moment in lb. in.,
and θ = angle of twist corresponding to appropriate twisting moment in any units.

For the majority of moist soils which have been tested to date (Figs. 3 to 5) the simplified equation (b) has given results for the maximum shear strength very close to the answer obtained from equation (a):

$$s = \frac{3M}{2\pi r^3}. \qquad \text{(b)}$$

The experimental and mathematical work involved is very much reduced, since the angle of twist need not be measured, and it is thus possible to dispense with the pointer (D). The error in using this simplified formula

occurs because, as will be seen from a comparison of Figs. 2 (*a*) and 2 (*b*), the maximum shear stress does not coincide exactly with the angle of twist corresponding to the maximum torque.

Theory

Casagrande (1948) has shown that the strength of sands is only negligibly affected by the rate at which they are strained; but that with such large increases as, say, 10,000 times, the strength of clays may be increased by up to 100 per cent. At the other extreme, where the rate of straining has been 10,000 times less, Taylor (1943) and Casagrande and Wilson (1949) have shown the reduction in strength to be only of the order of 15 to 30 per cent. Small variations in the rate of straining of 5 times greater or smaller than the normal have been studied by Skempton (1950), and the maximum variations in strength recorded were 10 per cent. Little error, then, should be introduced into soil strength measurements related to implement draught if the rate of straining be standardized at some convenient level approximating to the normal speed of cultivation. Since, moreover, approximately 90 per cent. of the torque is contributed by that thick annulus from half-way along the radius to the skin, the error involved in the change of rate of strain within the disk should be negligible.

Assumptions

1. A pure twisting couple is set up in that short part of the cylinder of soil between the main bulk of the land and that part of the cylinder within the shear box.

2. The whole of the normal load applied to the top of the box is distributed evenly over the shearing plane so that none is borne by the cutting edges.

3. The rate of straining over the range occurring has but negligible effect on strength.

Let r = radius of torsion box,
h = distance between bottom edge of box and bulk of land for any test.

Now for any value of M—the twisting couple—
let θ = angle of twist,
ϕ = shear strain,
and s = shear stress.

Consider the equilibrium of any elementary ring of thickness δx and radius x.

Then
$$\phi = \theta \frac{x}{h}, \tag{1}$$

$$s = f(\phi) \text{ (unknown)}. \tag{2}$$

For any angle of twist, the force on this ring

$$= 2\pi x \delta x \, s,$$

which from (2) $= 2\pi x \delta x f(\phi)$.

Therefore δM, the moment on this ring,

$$= 2\pi x^2 \delta x f(\phi),$$

or summing for the whole disk

$$M = \int_0^r 2\pi x^2 f(\phi)\, dx. \tag{3}$$

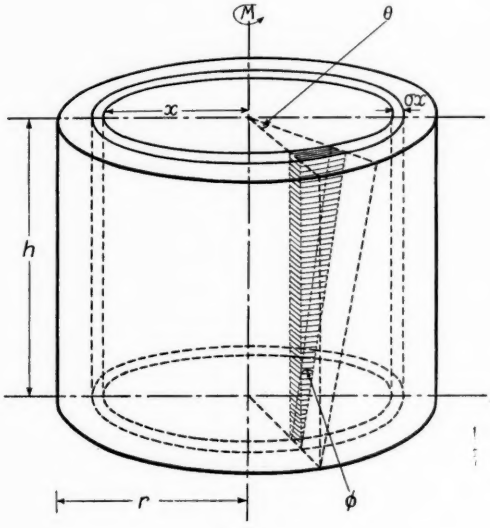

FIG. 3.

Now considering the whole tube of which the cross-section is that of the elementary ring; the rate of change of the moment with respect to the angle of twist

$$= \frac{dM}{d\theta} = \int_0^r 2\pi x^2 \frac{d}{d\theta} f(\phi)\, dx, \tag{4}$$

but from (1), $f(\phi) = f\left(\frac{x\theta}{h}\right)$;

moreover, the angle of twist and the radius are independent variables.

Therefore $$\frac{d}{d\theta} f\left(\frac{x\theta}{h}\right) = f'\left(\frac{x\theta}{h}\right)\frac{x}{h} \tag{5}$$

and $$\frac{d}{dx} f\left(\frac{x\theta}{h}\right) = f'\left(\frac{x\theta}{h}\right)\frac{\theta}{h}. \tag{6}$$

Therefore from (6) $$f'\left(\frac{x\theta}{h}\right) = \frac{d}{dx} f\left(\frac{x\theta}{h}\right)\frac{h}{\theta},$$

and from (5) $$\frac{d}{d\theta} f\left(\frac{x\theta}{h}\right) = \frac{d}{dx} f\left(\frac{x\theta}{h}\right)\frac{x}{\theta}. \qquad (7)$$

Therefore from (7), (4) becomes

$$\frac{dM}{d\theta} = \int_0^r \frac{2\pi x^3}{\theta}\frac{d}{dx} f\left(\frac{x\theta}{h}\right) dx = \left[\frac{2\pi x^3}{\theta} f\left(\frac{x\theta}{h}\right)\right]_0^r - \int_0^r f\left(\frac{x\theta}{h}\right)\frac{3}{\theta}\, 2\pi x^2\, dx,$$

but, from (3), $$\frac{3}{\theta}\int_0^r f\left(\frac{x\theta}{h}\right) 2\pi x^2\, dx = \frac{3}{\theta} M,$$

and, from (2), $$f\left(\frac{x\theta}{h}\right) = s.$$

Therefore $$\frac{dM}{d\theta} = \frac{2\pi r^3}{\theta} s - \frac{3}{\theta} M.$$

Therefore $$s = \frac{3}{2\pi r^3}\left(M + \frac{\theta}{3}\frac{dM}{d\theta}\right). \qquad (8) \text{ and } (a)$$

Note: Hvorslev (1939) obtained a result of the same form for an annulus by a somewhat different mathematical treatment.

Tests

The apparatus has been used on a wide range of top soils and plots of maximum shear strength against normal load have been obtained. Figs. 4–6 are examples. The only serious difficulties met have been on soils which contained a high proportion of large stones or undecayed organic matter, when the scatter of the readings was excessive.

Some results found with the torsion box have been compared with those from a standard shear box (Figs. 4 and 5). As would be expected from a sample which has not been weakened by removal, the cohesion, as recorded by the torsion box, was in most cases higher than that recorded by the standard box, while both techniques gave much the same angle of shearing resistance.

Note: A fuller description of the whole work and more results are given in Technical Memorandum No. 42 of the National Institute of Agricultural Engineering.

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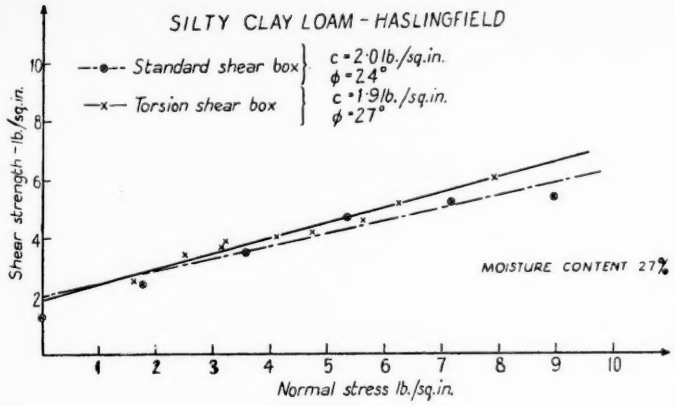

FIG. 4.

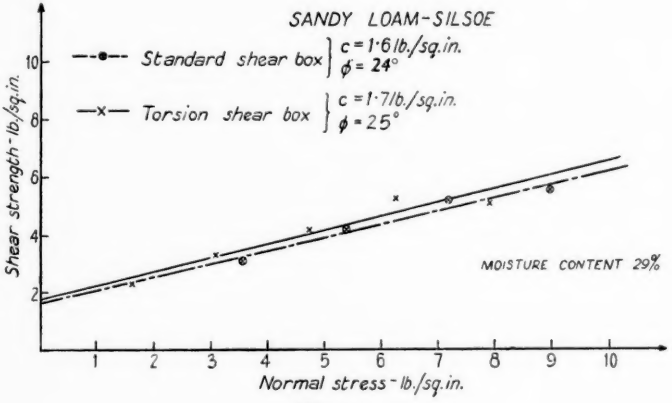

FIG. 5.

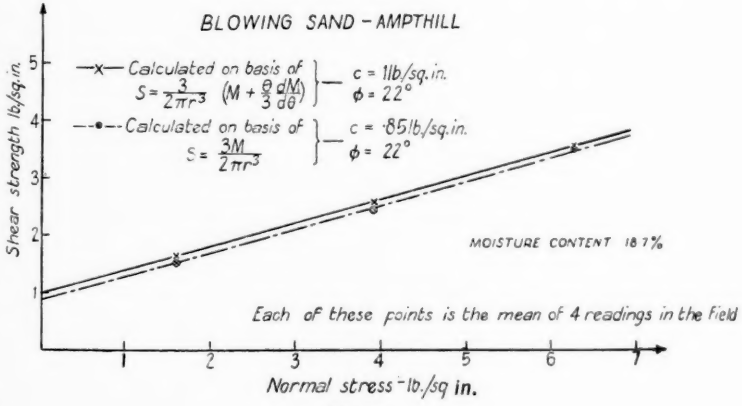
BLOWING SAND - AMPTHILL
Calculated on basis of S = 3/(2πr³) (M + θ/3 dM/dθ)
c = 1 lb./sq.in.
φ = 22°
Calculated on basis of S = 3M/(2πr³)
c = ·85 lb./sq.in.
φ = 22°
MOISTURE CONTENT 18·7%
Each of these points is the mean of 4 readings in the field
Shear strength lb./sq.in.
Normal stress - lb./sq in.

FIG. 6.

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